

Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus



A Joint Study Sponsored by:

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Final Report
May 1998**

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Executive Summary

What is biodiesel?

Biodiesel is a renewable diesel fuel substitute. It can be made from a variety of natural oils and fats. Biodiesel is made by chemically combining any natural oil or fat with an alcohol such as methanol or ethanol. Methanol has been the most commonly used alcohol in the commercial production of biodiesel. In Europe, biodiesel is widely available in both its neat form (100% biodiesel, also known as B100) and in blends with petroleum diesel. European biodiesel is made predominantly from rapeseed oil (a cousin of canola oil). In the United States, initial interest in producing and using biodiesel has focused on the use of soybean oil as the primary feedstock mainly because the United States is the largest producer of soybean oil in the world.

Why biodiesel?

Proponents of biodiesel as a substitute for diesel fuel (in blends or in its neat form) can point to a number of potential advantages for biodiesel that could support a number of strategies for addressing national issues.

- ✓ ***Reducing dependence on foreign petroleum...***

Petroleum imports are at record levels in the United States, and will continue to rise as domestic supplies of oil shrink. Our transportation sector relies almost exclusively on petroleum as a source of energy. This is due to the high level of demand for gasoline and diesel fuel. Biodiesel can be produced domestically from agricultural oils and from waste fats and oils. With its ability to be used directly in existing diesel engines, biodiesel offers the immediate potential to reduce our demand for petroleum in the transportation sector.

- ✓ ***Leveraging limited supplies of fossil fuels....***

Regardless of whose perspective one chooses to believe on the future supply of coal, oil and natural gas, it is indisputable that the supply of these fuels is, ultimately, limited. Biodiesel has the potential to leverage our use of limited supplies of fossil fuels.

- ✓ ***Mitigating greenhouse gas emissions....***

The burning of fossil fuels over the past century has dramatically increased the levels of carbon dioxide (CO₂) and other “greenhouse gases” that trap heat in our atmosphere. The implications of the increasing levels of these greenhouse gases are a matter of serious debate. What is not questioned is that the levels of these greenhouse gases have risen at unprecedented rates in the context of geological time¹. To the extent that biodiesel is truly renewable, it could play a role in reducing greenhouse gas emissions from the transportation sector.

¹Revelle published the groundbreaking work on atmospheric CO₂ build-up during the International Geophysical Year of 1957, in which he stated the problem of greenhouse gases more clearly than any researcher before or since. He stated that “Human beings are carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be produced in the future. Within a few centuries, we are returning to the atmosphere and

✓ ***Reducing Air Pollution and Related Public Health Risks....***

One of EPA's primary charges is to reduce public health risks associated with environmental pollution. Biodiesel can play a role in reducing emissions of many air pollutants, especially those targeted by EPA in urban areas. These include emissions of particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), sulfur oxides (SO_x), nitrogen oxides (NO_x) and air toxics.

✓ ***Benefiting our domestic economy....*** Spending on foreign imports of petroleum send dollars out of our economy. Biodiesel offers the potential to shift this spending from foreign imports to domestically produced energy. It also offers new energy-related markets to farmers.

Why a life cycle study?

The purpose of this study is to quantify, to the extent possible, some of the benefits listed above. In this study, we have focused on those benefits related to biodiesel energy's balance, its effect on emissions of greenhouse gases, and its effects on the generation of air, water and solid waste pollutants. We have made no attempt to quantify domestic economic benefits of using biodiesel.

The effect of biodiesel on overall consumption of petroleum and other fossil fuels can only be understood in the context of this fuel's "life cycle"—the sequence of steps involved in making and using the fuel from the extraction of all raw materials from the environment to the final end-use of the fuel in an urban bus. Similarly, the accumulation of CO₂ in the atmosphere is a global effect that requires a comprehensive life cycle analysis. Furthermore, understanding the benefits of biodiesel means understanding how its life cycle emissions compare to those of petroleum diesel.

This study provides a life cycle inventory of environmental and energy flows to and from the environment for both petroleum diesel and biodiesel, as well as for blends of biodiesel with petroleum diesel.

The scope of this study

Life cycle analysis is a complex science. The level of detail required in such a study forces a high degree of specificity in the scope and application of the products being studied. A substantial amount of information from engine tests and fuel demonstrations of soybean-derived biodiesel in urban buses is available. We relied on this recent data and experience to characterize the performance of soybean-derived biodiesel in this application.

Findings

Conducting life cycle inventories is fraught with difficulties. Incomplete data is the rule rather than the exception. There are varying degrees of confidence in the results that we present in this report. The most reliable conclusions of this study are for overall energy balance and carbon dioxide emissions. For these two measures, our data is the most complete. More importantly, our sensitivity studies show that the estimates of carbon dioxide emissions and energy requirements are very robust-- that is, these results show little change in response to changes in key assumptions.

the oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years.”
Revelle, R.; Suess, H. *Tellus*, Volume 9, No. 11, pp 18-21. 1957.

Reductions in Petroleum and Fossil Energy Consumption

As one component of a strategy for reducing petroleum oil dependence and minimizing fossil fuel consumption, the use of biodiesel offers tremendous potential.

Substituting 100% biodiesel (B100) for petroleum diesel in buses reduces the life cycle consumption of petroleum by 95%. This benefit is proportionate with the blend level of biodiesel used. When a 20% blend of biodiesel and petroleum diesel (B20) is used as a substitute for petroleum diesel in urban buses, the life cycle consumption of petroleum drops 19%.

In our study, we found that the production processes for biodiesel and petroleum diesel are almost identical in their efficiency of converting a raw energy source (in this case, petroleum and soybean oil) into a fuel product. The difference between these two fuels is in the ability of biodiesel to utilize a renewable energy source.

Biodiesel yields 3.2 units of fuel product energy for every unit of fossil energy consumed in its life cycle. The production of B20 yields 0.98 units of fuel product energy for every unit of fossil energy consumed.

By contrast, petroleum diesel's life cycle yields only 0.83 units of fuel product energy per unit of fossil energy consumed. Such measures confirm the "renewable" nature of biodiesel.

Reductions in CO₂ Emissions

Given the low demand for fossil energy associated with biodiesel, it is not surprising that biodiesel's life cycle emissions of CO₂ are substantially lower than those of petroleum diesel.

Biodiesel reduces net emissions of CO₂ by 78.45% compared to petroleum diesel. For B20, CO₂ emissions from urban buses drop 15.66%.

In addition, biodiesel provides modest reductions in total methane emissions, compared to petroleum diesel. Methane is another, even more potent, greenhouse gas. Thus, use of biodiesel to displace petroleum diesel in urban buses is an extremely effective strategy for reducing CO₂ emissions.

Changes in Air Pollutant Emissions

The effect of biodiesel on air quality is more complex. Biodiesel, as it is available today, offers substantial improvements in some air pollutants, while it leads to increases in others.

Reductions in Particulates, Carbon Monoxide and Sulfur Oxides...

The use of B100 in urban buses results in substantial reductions in life cycle emissions of total particulate matter, carbon monoxide and sulfur oxides (32%, 35% and 8% reductions, respectively, relative to petroleum diesel's life cycle).

All three of these pollutants have been targeted by EPA because of the important role they play in public health risks, especially in urban areas where the acute effects of these pollutants may be greater. Given the concern over urban air quality, it is important to note that most of these reductions occur because of lower emissions at the tailpipe. For buses operating in urban areas, this translates to an even greater potential benefit:

Tailpipe emissions of particulates less than 10 microns in size are 68% lower for buses run on biodiesel (compared to petroleum diesel). In addition, tailpipe emissions of carbon monoxide are 46% lower for buses run on biodiesel (compared to petroleum diesel). Biodiesel completely eliminates emissions of sulfur oxides at the tailpipe.

Tailpipe emissions of particulates that are smaller than 10 microns in size are specifically regulated by EPA because of the tendency for fine particulate matter to remain trapped in the lungs.

The reductions in air emissions reported here are proportional to the amount of biodiesel present in the fuel. Thus, for B20, users can expect to see 20% of the reductions reported for biodiesel used in its neat form (B100).

Increased Emissions of Nitrogen Oxides (NO_x)...

NO_x is one of three pollutants implicated in the formation of ground level ozone and smog in urban areas (NO_x, CO and hydrocarbons).

The use of B100 in urban buses increases life cycle emissions of NO_x by 13.35%. Blending biodiesel with petroleum proportionately lowers NO_x emission. B20 exhibits a 2.67% increase in life cycle emissions of NO_x. Most of this increase is directly attributable to increases in tailpipe emissions of NO_x. B100, for example, increases tailpipe levels of NO_x by 8.89%.

Our results are presented for fuel and engine technology as they exist today. Our study points out the need for research on both engine design and biodiesel fuel formulation to address this problem.

Hydrocarbons—higher on a life cycle basis, but lower at the tailpipe...

The increase in hydrocarbon emissions is due to release of hexane in the processing of soybeans and volatilization of agrochemicals applied on the farm.

Total life cycle emissions of hydrocarbons are 35% higher for B100, compared to petroleum diesel. However, emissions of hydrocarbons at the tailpipe are actually 37% lower.

These results point out opportunities for improving the life cycle of biodiesel. Future biodiesel research should focus on ways of reducing hexane releases from today's current levels in soybean crushing plants. Improvements in use of agrochemicals on the farm would have similarly beneficial effects.

Next Steps

At the outset, we designed this study to identify and quantify the advantages of biodiesel as a substitute for petroleum diesel. These advantages are substantial, especially in the area of energy security and control of greenhouse gases. We have also identified weaknesses or areas of concern for biodiesel—such as its emissions of NO_x and hydrocarbons. We see these as opportunities for further research to resolve these concerns. We hope that our findings will be used to focus future biodiesel research on these critical issues.

There is much that could be done to build on and improve the work we have done here. Appropriate next steps for this work include the following:

- **Use the life cycle inventory to assess the relative effects of petroleum diesel and biodiesel on our environment and on public health risks in order to gain an understanding of the benefits associated with biodiesel.**
- **Quantify the costs and benefits of biodiesel.**
- **Assess the economic impact of biodiesel as an alternative fuel (e.g., its effects on jobs, trade deficit, etc.)**
- **Evaluate other feedstock sources.**
- **Incorporate new health effects data on hydrocarbon emissions from biodiesel and petroleum diesel.**
- **Develop regional life cycle models for biodiesel use.**
- **Evaluate performance of newer diesel engines and new fuel production technologies.**

Table of Contents

1	<i>How To Use This Report</i>	1
2	<i>Technical Overview</i>	3
2.1	Stakeholder Involvement	3
2.2	Scope of the Life Cycle Study	4
2.2.1	Purpose	4
2.2.2	What Is “Biodiesel?”	4
2.2.3	What Is “Petroleum Diesel?”	5
2.2.4	Defining the Product Application	5
2.2.5	What Is Included in the Life Cycle Systems?	5
2.2.6	What Are the Geographical Boundaries?	6
2.2.7	What Is the Time Frame?	6
2.2.8	Basis for Comparing the Life Cycles	6
2.3	Key Assumptions	8
2.4	Findings	8
2.4.1	Results of the Base Case Study	9
2.4.1.1	Life Cycle Energy Balance	10
2.4.1.1.1	Types of Life Cycle Energy Inputs	10
2.4.1.1.2	Defining Energy Efficiency	11
2.4.1.1.3	Petroleum Diesel Life Cycle Energy Consumption	11
2.4.1.1.4	Biodiesel Life Cycle Energy Demand	13
2.4.1.1.5	Effect of Biodiesel on Life Cycle Energy Demands	17
2.4.1.2	CO ₂ Emissions	18
2.4.1.2.1	Accounting for Biomass-Derived Carbon	18
2.4.1.2.2	Comparison of CO ₂ Emissions for Biodiesel and Petroleum Diesel	18
2.4.1.3	Primary Resource Consumption for Biodiesel and Petroleum Diesel	19
2.4.1.4	Life Cycle Emissions of Regulated and Nonregulated Air Pollutants	22
2.4.1.4.1	Comparison of Life Cycle Air Emissions for Biodiesel and Petroleum Diesel	23
2.4.1.5	Life Cycle Emissions of Water Effluents	25
2.4.1.6	Comparison of Solid Waste Life Cycle Flows	26
2.4.2	Sensitivity Studies	27
2.4.2.1	The Effect of Enhanced Location for Biodiesel Production and Use	27
2.4.2.2	The Effect of Energy Requirements for Conversion of Soybean Oil to Biodiesel	30
2.5	Conclusions	33
2.5.1	Life Cycle Energy and Environmental Flows	33
2.5.2	Next Steps	34
3	<i>Life Cycle Scope and Methodology</i>	35
3.1	Background	35
3.1.1	Life Cycle Assessment Overview	35
3.1.2	Biodiesel and Petroleum Diesel Fuels	36
3.2	Purpose of this Study	37
3.3	Project Scope	37
	Project Parameters	37
3.3.1.1	Environmental Issues Considered	37
3.3.1.2	Temporal Scope	39
3.3.1.3	Geographical Scope	39

3.3.2	Product Parameters.....	40
3.3.2.1	Fuels Studied	40
3.3.2.2	End-Use.....	41
3.3.2.3	Functional Unit.....	41
3.3.3	Process Parameters.....	41
3.3.3.1	Biodiesel.....	41
3.3.3.2	Petroleum Diesel Fuel	42
3.3.4	LCA-Specific Parameters	42
3.4	System Boundaries	43
3.4.1	LCA Principle for Setting System Boundaries.....	43
3.4.2	How Allocation Rules are Used in Our Study.....	45
4	<i>Petroleum Diesel Fuel Modeling</i>	53
4.1	Petroleum Diesel Fuel General Modeling Assumptions	53
4.1.1	Geographic Boundaries	53
4.2	Crude Oil Extraction.....	54
4.2.1	Conventional Onshore Extraction	55
4.2.1.1	Material Use	55
4.2.1.2	Energy/Equipment Use.....	56
4.2.1.3	Process Emissions.....	57
4.2.1.4	Crude Oil Separation.....	58
4.2.1.5	Crude Oil and Natural Gas Allocations – Conventional Onshore.....	59
4.2.2	Conventional Offshore Extraction.....	61
4.2.2.1	Material Use	61
4.2.2.2	Energy/Equipment Use.....	61
4.2.2.3	Process Emissions.....	62
4.2.2.4	Crude Oil Separation.....	64
4.2.2.5	Crude Oil and Natural Gas Allocations – Conventional Offshore	64
4.2.3	Advanced Onshore Extraction (Steam Injection).....	65
4.2.3.1	Material Use	66
4.2.3.2	Energy/Equipment Use.....	66
4.2.3.3	Process Emissions.....	66
4.2.3.4	Crude Oil and Natural Gas Allocation-Steam Injection Extraction	67
4.2.4	Advanced Onshore Extraction (CO ₂ Injection).....	67
4.2.4.1	Material Use	67
4.2.4.2	Energy/Equipment Use.....	68
4.2.4.3	Process Emissions.....	68
4.2.4.4	Crude Oil and Natural Gas Allocations - CO ₂ injection	69
4.2.5	Crude Oil Extraction Results	69
4.3	Crude Oil Transport to Refinery	72
4.3.1	Transportation Regionalization.....	72
4.3.2	Transportation Distances	73
4.3.3	Transportation Models.....	75
4.3.4	Energy and Fugitive Emissions from Storage and Handling	75
4.3.5	Crude Oil Transportation Results.....	80
4.4	Crude Oil Refining.....	83
4.4.1	Material Use.....	85
4.4.2	Energy/Equipment Use.....	86
4.4.3	Process Emissions	87
4.4.3.1	Air Emissions	87
4.4.3.2	Water Effluents.....	88
4.4.3.3	Solid Waste	88
4.4.4	Diesel Fuel Production	90

4.4.5	Crude Oil Refining Results.....	91
4.5	Diesel Fuel Transport.....	93
4.5.1	Modes of Transport and Distance Transported	93
4.5.2	Energy and Fugitive Emissions from Storage and Handling	94
4.5.3	Diesel Fuel Transportation Results.....	94
5	Biodiesel Fuel Modeling.....	97
5.1	Soybean Agriculture.....	97
5.1.1	Soybean Agriculture General Modeling Assumptions	98
5.1.2	Soybean Agriculture Materials Consumption	99
5.1.2.1	Fertilizers and Agrochemicals	99
5.1.2.2	Water Use	102
5.1.3	Soybean Agriculture Energy and Equipment Use	102
5.1.3.1	Energy Use and Soybean Yield	102
5.1.3.2	Energy Emissions	105
5.1.4	Soybean Agriculture Biological Interactions/Field Emissions.....	105
5.1.4.1	Soil Erosion—National Resource Inventory.....	106
5.1.4.2	Other Nutrients and Fertilizers Carried off the Field by Erosion	107
5.1.4.3	Agrochemicals in Waterways	109
5.1.4.4	Agrochemicals in the Atmosphere	111
5.1.4.5	NOx and N ₂ O Emissions from Soil.....	114
5.1.5	Soybean Agriculture LCI Results.....	115
5.2	Soybean Transport to Crusher	117
5.2.1	Modes of Transport and Distance Transported	117
5.2.2	Energy and Fugitive Emissions from Storage and Handling	117
5.2.3	Soybean Transportation Results.....	117
5.3	Soybean Crushing	119
5.3.1	Process Description for Soybean Crushing.....	119
5.3.1.1	Soybean Receiving and Storage.....	121
5.3.1.2	Bean Preparation.....	122
5.3.1.3	Soybean Oil Extraction	124
5.3.1.4	Meal Processing.....	125
5.3.1.5	Soybean Oil Recovery	127
5.3.1.6	Solvent Recovery	128
5.3.1.7	Oil Degumming	128
5.3.1.8	Waste Treatment.....	130
5.3.2	Analysis of Yields and Energy Balance.....	131
5.3.3	Overall Inputs to Soybean Crushing.....	133
5.3.4	Overall Soybean Crushing Outputs	134
5.3.5	Allocation of Life Cycle Flows for Soybean Crushing.....	136
5.3.6	Soybean Crushing Results	136
5.4	Soybean Oil Transport.....	138
5.4.1	Where Do We Locate the Biodiesel Conversion Facilities?	138
5.4.2	Modes of Transport and Distance Transported	139
5.4.3	Energy and Fugitive Emissions from Storage and Handling	139
5.4.4	Soybean Oil Transport Results.....	140
5.5	Soybean Oil Conversion.....	142
5.5.1	Process Overview for Conversion of Soybean Oil to Biodiesel	142
5.5.1.1	Alkali Refining of Crude Soybean Oil	144
5.5.1.2	Transesterification	147
5.5.1.3	Methyl Ester Purification	148
5.5.1.4	Glycerine Recovery.....	150

5.5.1.5	Methanol Recovery	154
5.5.1.6	Waste Treatment.....	157
5.5.2	Analysis of Yields and Energy Balance.....	158
5.5.3	Overall Inputs to the Soybean Oil Conversion Facility	163
5.5.4	Overall Soybean Oil Conversion Outputs.....	164
5.5.5	Allocation of Life Cycle Flows for Soy Oil Conversion to Biodiesel	165
5.5.6	Soybean Conversion Results.....	165
5.6	Biodiesel Transport.....	167
5.6.1	Modes of Transport and Distance Transported	167
5.6.2	Energy and Fugitive Emissions from Storage and Handling	167
5.6.3	Biodiesel Transportation Results.....	167
6	Urban Bus Operation.....	171
6.1	Biodiesel Fuel Combustion.....	171
6.1.1	Comparison of Fuel Properties of Petroleum Diesel and Biodiesel.....	171
6.1.1.1	Cetane Number.....	174
6.1.1.2	Flash Point.....	174
6.1.1.3	Distillation.....	175
6.1.1.4	Specific Gravity	175
6.1.1.5	Energy Content.....	175
6.1.1.6	Flow Properties (Cold Temperature Sensitivity).....	175
6.1.1.7	Viscosity and Surface Tension	176
6.1.1.8	Oxidative Stability	176
6.1.1.9	Sulfur, Aromatic, Ash, Sediments, Water, Methanol, Glycerine, and Glyceride Content.....	177
6.1.1.10	Biodiesel Composition	177
6.1.2	Biodiesel Fuel Economy.....	177
6.1.3	Biodiesel Tailpipe Emissions.....	181
6.1.4	The Fate of Biomass Carbon Leaving the Tailpipe of the Bus.....	184
6.1.5	Biodiesel Combustion Results	186
6.2	Diesel Fuel Combustion.....	187
6.2.1	Diesel Fuel Economy.....	187
6.2.2	Tailpipe Emissions	187
6.3	Combustion End-use Results	187
7	Software Modeling Tools	189
7.1	Description of the TEAM™ Model.....	189
1.2	Description of the Database Used	189
1.2.1	Electricity.....	189
1.2.1.1	Electricity from Coal.....	190
1.1.1.1.1	Coal Mining	190
1.1.1.1.2	Cleaning and Preparation	191
1.1.1.1.3	Transportation from Site of Extraction to Power Plant	191
1.1.1.1.4	Coal–Rail	191
1.1.1.1.5	Coal–Truck	191
1.1.1.1.6	Coal–Ship.....	192
1.1.1.1.7	Coal Slurry Pipeline.....	192
1.1.1.1.8	Water Effluents.....	192
1.1.1.2	Coal Combustion	192
1.1.1.2.1	Emissions Control Technology.....	194
1.1.1.2.2	Water Effluents.....	194
1.1.1.3	Post-Combustion Products of Coal	194
1.1.1.3.1	Transportation to the Landfill from the Silo	195
1.1.1.4	Electricity from Heavy Fuel Oil	195

1.1.1.5	Electricity from Natural Gas	195
1.1.1.6	Natural Gas Production	195
1.1.1.6.1	Mining and Cleaning Natural Gas	195
1.1.1.6.2	Gas Sweetening	196
1.1.1.6.3	Transportation	196
1.1.1.7	Natural Gas Combustion	196
1.1.1.8	Electricity from Nuclear Energy	197
1.1.1.9	Electricity from Hydroelectric Power	197
1.1.1.10	Electricity per Geographical Zone	197
1.1.2	Fertilizers and Agrochemicals.....	199
8	<i>Data Quality.....</i>	203
9	<i>Results and Discussion</i>	205
9.1	Base Case Results	206
9.1.1	Life Cycle Energy Balance	206
9.1.1.1.1	Types of Life Cycle Energy Inputs	206
9.1.1.1.2	Defining Energy Efficiency	207
9.1.1.2	Petroleum Diesel Life Cycle Energy Consumption	208
9.1.1.3	Biodiesel Life Cycle Energy Demand.....	211
9.1.1.4	Effect of Biodiesel on Life Cycle Energy Demands	213
9.1.2	CO ₂ Emissions	215
9.1.2.1	Accounting for Biomass-Derived Carbon	215
9.1.2.2	Petroleum Diesel Life Cycle Emissions of CO ₂	217
9.1.2.3	Biodiesel Life Cycle Emissions of CO ₂	220
9.1.2.4	The Effect of Biodiesel on CO ₂ Emissions from Urban Buses	221
9.1.3	Life Cycle Consumption of Primary Resources	222
9.1.3.1	Life Cycle Consumption of Primary Resources for Petroleum Diesel	222
9.1.3.2	Life Cycle Consumption of Primary Resources for Biodiesel	225
9.1.3.3	The Effect of Biodiesel on Primary Resource Consumption	228
9.1.4	Life Cycle Emissions of Regulated and Nonregulated Air Pollutants	231
9.1.4.1	Life Cycle Air Emissions from Petroleum Diesel Life Cycle	231
9.1.4.2	Life Cycle Emissions of Air Pollutants for Biodiesel.....	239
9.1.4.3	Comparison of Life Cycle Air Emissions from Biodiesel and Petroleum Diesel.....	251
9.1.4.4	Potential Effects of Biodiesel as a Diesel Substitute on Life Cycle Air Emissions.....	256
9.1.4.5	Tailpipe Emissions for Petroleum Diesel and Biodiesel.....	258
9.1.5	Life Cycle Emissions of Water Effluents	261
9.1.6	Life Cycle Flows of Solid Waste	263
9.2	Sensitivity Studies.....	267
9.2.1	The Effect of an Enhanced Location for Biodiesel Production and Use	268
9.2.2	The Effect of Energy Requirements for Conversion of Soybean Oil to Biodiesel	272
10	<i>Appendix A: Emission Factors</i>	277
11	<i>Appendix B: References.....</i>	279
	Life Cycle Scope and Approach.....	279
	Petroleum Diesel Fuel Production	280
	Soybean Agriculture	281
	Soybean Crushing	282
	Soybean Oil Conversion.....	282
	Combustion	284

Tables

Table 1: Geographic Scope of the Petroleum Diesel Life Cycle	7
Table 2: Geographic Scope of the Biodiesel Life Cycle	7
Table 3: Primary Energy Requirements for the Petroleum Diesel Life Cycle	12
Table 4: Fossil Energy Requirements for the Petroleum Diesel Life Cycle	14
Table 5: Primary Energy Requirements for Biodiesel Life Cycle	15
Table 6: Fossil Energy Requirements for the Biodiesel Life Cycle	17
Table 7: Tailpipe Contribution to Total Life Cycle CO ₂ for Petroleum Diesel and Biodiesel (g CO ₂ /bhp-h)	19
Table 8: Model Parameters for the Chicago Area Biodiesel Scenario	28
Table 9: Range of Energy Inputs for Soybean Oil Conversion Tested in LCI Model	30
Table 10: LCI Items Considered	38
Table 11: Geographic Scope of Petroleum Diesel Fuel Modeling	40
Table 12: Geographic Scope of Biodiesel Modeling	40
Table 13: Environmental Inflows and Outflows for the Biodiesel Conversion Process	45
Table 14: Mass Percent of the Various Conversion Co-Products	45
Table 15: Mass Allocated Conversion Results for Biodiesel	46
Table 16: Mass Allocated Conversion Results for Glycerine (not used in this study)	47
Table 17: Biodiesel Conversion Process Flows per Coproduct	47
Table 18: Production of Crude Oil by Technology Type and Origin	55
Table 19: Crude Oil Production Wastewater Constituents and Concentrations	57
Table 20: Natural Gas Venting and Flaring from Onshore Crude Oil Wells	58
Table 21: VOC Emissions for Onshore Crude Oil Wells	59
Table 22: Speciated VOC Data for Onshore Crude Oil Wells	59
Table 23: Natural Gas Venting, Flaring, and Coproduct Production from Onshore Crude Oil Wells	60
Table 24: Production of Typical Domestic Conventional Onshore Crude Oil Well	60
Table 25: Production of Typical Foreign Conventional Onshore Crude Oil Well	60
Table 26: Natural Gas Venting and Flaring from Offshore Crude Oil Wells	63
Table 27: Speciated VOC Emissions for Offshore Crude Oil Production	63
Table 28: Natural Gas Venting, Flaring, and Coproduct Production from Offshore Crude Oil Wells	64
Table 29: Production of Typical Domestic Conventional Offshore Crude Oil Well	65
Table 30: Production of Typical Foreign Conventional Offshore Crude Oil Well	65
Table 31: LCI Results for Domestic Crude Oil Extraction (for 1 kg of crude oil)	70
Table 32: LCI Results for Foreign Crude Oil Extraction (for 1 kg of crude oil)	71
Table 33: Refinery Receipts of Crude Oil by Source and by PADD (1993)	72

Table 34: Refinery Receipts of Crude Oil by Method of Transportation and by PADD (1993).....	73
Table 35: LCI Results for Domestic Crude Oil Transportation (for 1 kg of crude oil)	81
Table 36: LCI Results for Foreign Crude Oil Transportation (for 1 kg of crude oil)	82
Table 37: Mass and Energy Balance Calculations for an Average U.S. Refinery.....	84
Table 38: Material Requirements for an Average U.S. Refinery	85
Table 39: Material Requirements for an Average U.S. Refinery	86
Table 40: Internal Energy Use for an Average U.S. Refinery.....	86
Table 41: Petroleum Refining Process Emissions	88
Table 42: Refinery Process Flows	88
Table 43: Wastewater Production in Crude Oil Refineries	89
Table 44: Crude Oil Refinery Wastewater Composition	89
Table 45: Solid Waste Produced from Crude Oil Refining.....	89
Table 46: Total U.S. Refinery Production (1994)	90
Table 47: LCI Results for Crude Oil Refining (for 1 kg of diesel produced)	92
Table 48: LCI Results for Diesel Fuel Transportation (for 1 kg of diesel fuel)	96
Table 49: Soybean Agriculture System Inputs.....	101
Table 50: Irrigation Water Used on Soybeans by State per Year (1994).....	102
Table 51: Average Soybean Yield (Bu/acre/yr)	103
Table 52: Soybean Production by State	104
Table 53: Emission Factors for Diesel Fuel Combustion in a Farming Tractor.....	105
Table 54: Emission Factors for Gasoline Combustion in a Farming Tractor.....	105
Table 55: Estimated Annual Average Sheet and Rill Erosion on Total Cropland and Soybean Cropland—1992	107
Table 56: Estimated Annual Average Wind Erosion on Total Cropland and Soybean Cropland—1992	108
Table 57: Annual Erosion and Discharge of TSS, TKN, and TP on Soybean Acreage.....	109
Table 58: Amounts and Types of Herbicides Applied to Soybean Agriculture	112
Table 59: Weighted Average Vapor Pressure of Surface-Applied Agrochemicals.....	113
Table 60: VOC Emission Factors for Soil-Incorporated Agrochemicals.....	113
Table 61: VOC Emission Factors for Surface-Applied Agrochemicals	114
Table 62: LCI Results for Soybean Agriculture (for 1 kg of soybeans)	116
Table 63: LCI Results for Soybean Transport (for 1 kg of soybeans).....	118
Table 64: Bean Composition.....	121
Table 65: Soybean Oil Composition.....	122
Table 66: Energy Requirements for Receiving and Storage in a Soybean Crushing Facility (normalized to 1 metric ton of beans).....	123

Table 67: Energy Requirements for Bean Preparation in a Soybean Crushing Facility (normalized per metric ton beans).....	124
Table 68: Electricity Requirements for Meal Processing in a Soybean Crushing Facility (kWh per metric ton of beans)	126
Table 69: Steam Requirements for Meal Processing in a Soybean Crushing Facility (kcal per metric ton of beans).....	126
Table 70: Electricity Requirements for Oil Recovery in a Soybean Crushing Facility (kWh per metric ton of beans).....	128
Table 71: Steam Requirements for Oil Recovery in a Soybean Crushing Facility (kcal per metric ton of beans).....	128
Table 72: Final Composition of Crude, Degummed Oil.....	129
Table 73: Electricity Requirements for Degumming in a Soybean Crushing Facility (kWh per metric ton of beans).....	129
Table 74: Steam Requirements for Degumming in a Soybean Crushing Facility (kcal per metric ton of beans).....	130
Table 75: Steam Requirements for Waste Treatment in a Soybean Crushing Facility (kcal per metric ton of beans).....	131
Table 76: Summary of Electricity Requirements for Soybean Crushing (kWh per metric ton of beans).	132
Table 77: Raw Material Inputs to Soybean Crushing Facility	134
Table 78: Energy Inputs to Soybean Crushing Process	134
Table 79: Products from Soybean Crushing Facility.....	134
Table 80: Air Emissions from Soybean Crushing Facility (Excluding Combustion).....	135
Table 81: Water Emissions from a Soybean Crushing Facility.....	135
Table 82: Production of a Generic Soybean Crushing Facility	136
Table 83: LCI Results for Soybean Crushing (for 1 kg of soybean oil)	137
Table 84: LCI Assumptions for Soy Oil Transportation.....	140
Table 85: LCI Results for Soybean Oil Transport (for kg soybean oil).....	141
Table 86: Tentative Biodiesel Fuel Specifications Proposed by The National Biodiesel Board.....	144
Table 87: Composition of Crude, Degummed Oil from Crushing Operation	145
Table 88: Losses Associated with Alkaline Refining of Crude, Degummed Soybean Oil	146
Table 89: Steam Requirements for Alkaline Refining of Crude, Degummed Oil (per metric ton of Biodiesel Produced)	146
Table 90: Steam Requirements for Transesterification (Normalized per Metric Ton of Biodiesel Produced).....	148
Table 91: Composition of Final Biodiesel Product Based on Material Balance	150
Table 92: Steam Requirements for Methyl Ester Purification (normalized per metric ton of biodiesel produced).....	150

Table 93: Steam Requirements for Glycerine By-Product Recovery (normalized per metric ton of biodiesel produced).....	154
Table 94: Steam Requirements for Methanol Recovery (normalized per metric ton of biodiesel produced)	157
Table 95: Electricity Requirements for Conversion of Crude Degummed Soybean Oil to Biodiesel	159
Table 96: Summary of Steam Requirements for Biodiesel Production (normalized per metric ton of biodiesel produced).....	159
Table 97: Reported Steam Usage in Kansas City Facility Used as a Starting Point for Our Model	160
Table 98: Comparison of Steam Requirements for Our Process Design Model and Other Available Technologies (kcal steam per metric ton of biodiesel).....	161
Table 99: Comparison of Electricity Requirements for Our Process Model and for Current European Technologies.....	162
Table 100: Raw Material Inputs to Biodiesel Production Facility	163
Table 101: Energy Inputs to a Biodiesel Production Facility.....	164
Table 102: Products from a Biodiesel Production Facility	164
Table 103: Water and Solid Waste Emissions from a Biodiesel Production Facility.....	164
Table 104: Production of a Generic Soybean Conversion Facility.....	165
Table 105: LCI Results for Soybean Oil Conversion (for 1 kg of biodiesel).....	166
Table 106: LCI Results for Biodiesel Transportation (for kg of biodiesel)	169
Table 107: Glossary of Terms for Fuel Properties	172
Table 108: Summary of Properties of Diesel and Various Biodiesel Esters	173
Table 109: Elemental Composition of Biodiesel and Petroleum Diesel	177
Table 110: Economy Data for Biodiesel Fuels in a Modern Series 60 Engine	178
Table 111: Fuel Economy Data for a Series of Engines Operating with Catalysts and Timing Changes	178
Table 112: Chassis Dynamometer-Based Fuel Economy Data.....	180
Table 113: Analytical Data for Soy Methyl Ester	185
Table 114: Percent Soot as a Function of Percent Oxygen in Fuel	185
Table 115: Effect of Biodiesel on Tailpipe Emissions (g/bhp-h)	186
Table 116: 1994 U.S. EPA Emission Standards for Diesel Engines versus Engine Certification Data for Two Common Urban Bus Engines (g/bhp-h).....	188
Table 117: Coal Fire Configurations Provided by the Interim Inventory (1994).....	193
Table 118: Coal Carbon and CO ₂ Emissions Factors	194
Table 119: Percent Horsepower for Pipeline Power in 1989	196
Table 120: Share of Power Generation Source by Region in North America.....	198
Table 121: Energy Content of Fertilizers and Agrochemicals	202
Table 122: Primary Energy Demand for the Petroleum Diesel Life Cycle Inventory	208

Table 123: Fossil Energy Requirements for the Petroleum Diesel Life Cycle.....	211
Table 124: Primary Energy Requirements for Biodiesel Life Cycle	212
Table 125: Fossil Energy Requirements for the Biodiesel Life Cycle.....	214
Table 126: Biomass Carbon Balance for Biodiesel Life Cycle (g/bhp-h).....	216
Table 127: LCI Inventory of Raw Material Consumption for Petroleum Diesel (kg/bhp-h).....	223
Table 128: Life Cycle Consumption of Primary Resources for Biodiesel	226
Table 129: LCI of Air Emissions for Petroleum Diesel (g/bhp-h)	232
Table 130: LCI Air Emissions for Biodiesel (g/bhp-h)	240
Table 131: Air Emissions for Petroleum Diesel, B20, and B100 (g/bhp-h).....	251
Table 132: Relative Change in Life Cycle Air Emissions for Fuels Containing 20% and 100% Biodiesel	256
Table 133: Baseline Diesel Engine Emissions for Low-Sulfur Petroleum Diesel.....	259
Table 134: Model Parameters for the Chicago Area Biodiesel Scenario.....	268
Table 135: Chicago Scenario Life Cycle Resource Demands for Biodiesel (kg/bhp-h).....	269
Table 136: Life Cycle Air Emissions for Chicago Area Biodiesel Scenario	270
Table 137: Life Cycle Water and Solid Emissions for the Chicago Area Biodiesel Scenario	271
Table 138: Range of Energy Inputs for Soybean Oil Conversion Tested in LCI Model	272
Table 139: The Effect of Soy Oil Conversion Energy Demands on Life Cycle Consumption of Raw Materials.....	273
Table 140: The Effect of Soybean Oil Conversion Energy Demands on Air Emissions from Biodiesel	274
Table 141: The Effect of Soybean Oil Conversion Energy Demands on Water and Solid Waste Emissions for Biodiesel (kg/bhp-h)	275
Table 142: Emission Factors for Natural Gas Combustion in an Industrial Boiler	277
Table 143: Emission Factors for Natural Gas Combustion in a Turbine	277
Table 144: Emission Factors for LPG Combustion in an Industrial Boiler	277
Table 145: Emission Factors for Coal Combustion in an Industrial Boiler	277
Table 146: Emission Factors for Diesel Oil Combustion in an Industrial Boiler.....	278
Table 147: Emission Factors for Heavy Fuel Oil Combustion in an Industrial Boiler.....	278
Table 148: Emission Factors for Natural Gas Combustion in an Industrial Flare.....	278

Figures

Figure 1: Ranking of Primary Energy Demand for the Stages of Petroleum Diesel Production.....	12
Figure 2: Process Energy Demand for Petroleum Diesel Life Cycle.....	13
Figure 3: Ranking of Fossil Energy Demand for Stages of the Petroleum Diesel Life Cycle	15
Figure 4: Ranking of Primary Energy Demand for Stages of the Biodiesel Life Cycle	16
Figure 5: Process Energy Requirements for Biodiesel Life Cycle	16
Figure 6: Fossil Energy Requirements versus Fuel Product Energy for the Biodiesel Life Cycle.....	17
Figure 7: Biomass Carbon Balance for Biodiesel Life Cycle (g carbon/bhp-h).....	20
Figure 8: Comparison of Net CO ₂ Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends.....	21
Figure 9: Petroleum Consumption for Petroleum Diesel, B20, and B100	21
Figure 10: Coal and Natural Gas Consumption for Petroleum Diesel, B20, and B100.....	22
Figure 11: Water Use for Petroleum Diesel, B20, and B100	22
Figure 12: Life Cycle Air Emissions for B100 and B20 Compared to Petroleum Diesel Life Cycle Air Emissions	24
Figure 13: Comparison of Total Wastewater Flows for Petroleum Diesel and Biodiesel Life Cycles.....	26
Figure 14: Hazardous Waste Generation for Petroleum Diesel, B20, and B100.....	27
Figure 15: Nonhazardous Waste Generation for Petroleum Diesel, B20, and B100.....	27
Figure 16: The Effect of an Enhanced Location for Biodiesel on Life Cycle Consumption of Primary Energy Resources.....	29
Figure 17 : Reductions in Life Cycle Air Emissions for the Chicago Area Biodiesel Scenario	29
Figure 18: Water and Solid Waste Emissions Reductions for the Chicago Area Biodiesel Scenario	30
Figure 19: The Effect of Conversion Energy Requirements on Primary Energy Resource Demands for Biodiesel.....	31
Figure 20: The Effect of Soybean Oil Conversion Energy Demands on Air Emissions for Biodiesel.....	32
Figure 21: The Effect of Soybean Oil Conversion Energy Demands on Water and Solid Waste Emissions for Biodiesel	32
Figure 22: Elements of the Scoping Phase for LCA.....	38
Figure 23: LCA System Boundary Principles	44
Figure 24: Primary Energy Balance for the Petroleum Diesel Fuel Life Cycle (with Mass Allocation)....	48
Figure 25: Primary Energy Balance for Petroleum Diesel Fuel Life Cycle (No Mass Allocation).....	49
Figure 26: Primary Energy Balance for Biodiesel Fuel Life Cycle (with Mass Allocation)	50
Figure 27: Primary Energy Balance for Biodiesel Fuel Life Cycle (No Mass Allocation).....	51
Figure 28: U.S. Crude Oil Production, Imports and Input to Refineries (1983-1994).....	54
Figure 29: Petroleum Process Areas Modeled in this Project	55
Figure 30: Conventional Onshore Crude Oil Extraction.....	56
Figure 31: Conventional Offshore Crude Oil Extraction	61

Figure 32: Advanced Onshore (Steam Injection) Crude Oil Extraction	65
Figure 33: Advanced Onshore (CO ₂ Injection) Crude Oil Extraction	67
Figure 34: Schematic of Crude Oil Production System Modeled in TEAM™	69
Figure 35: Modes of Transport and Distances for Crude Oil	76
Figure 36: Contributions to Life Cycle Flows for Transport and Handling of Crude Oil.....	79
Figure 37: Schematic of TEAM™ Model Inputs to Domestic Oil Transport	80
Figure 38: Schematic of TEAM Model Inputs to Foreign Oil Transport	80
Figure 39: Petroleum Refining System Description	83
Figure 40: Diesel Fuel Transportation Modeling	93
Figure 41: Diesel Fuel Transportation Modeling	95
Figure 42: Soybean Agriculture System Modeling	98
Figure 43: Schematic of TEAM™ Model Inputs to Soybean Agriculture	115
Figure 44: Soybean Crushing System Description	119
Figure 45: Overview of Soybean Crushing Process	120
Figure 46: Receiving and Storage in Soybean Crushing Facility	121
Figure 47: Bean Preparation in Soybean Crushing Facility	123
Figure 48: Oil Extraction in Soybean Crushing Facility	125
Figure 49: Meal Processing in Soybean Crushing Facility	126
Figure 50: Oil Recovery in Soybean Crushing Facility	127
Figure 51: Solvent Recovery in Soybean Crushing Facility	129
Figure 52: Oil Degumming Process for Soybean Crushing Facility	130
Figure 53: Waste Treatment for Soybean Crushing Facility	131
Figure 54: Yield of Oil and Triglycerides in a Soybean Crushing Facility.....	132
Figure 55: Distribution of Electricity Requirements in a Soybean Crushing Facility (kWh per metric ton of beans)	133
Figure 56: Steam and Natural Gas Consumption in a Soybean Crushing Facility (kcal per metric ton of beans)	133
Figure 57: Overview of Process for Conversion of Soybean Oil to Biodiesel (Flows in kg/h)	143
Figure 58: Alkali Refining of Crude Soybean Oil to Remove Free Fatty Acids.....	145
Figure 59: Transesterification Section of Biodiesel Production Facility	148
Figure 60: Methyl Ester Purification	149
Figure 61: Recovery of Crude Glycerine By-Product	151
Figure 62: ASPEN PLUS™ Sensitivity Study Results:.....	152
Figure 63: ASPEN PLUS™ Simulation Input Summary for Crude Glycerine Column.....	153
Figure 64: ASPEN PLUS™ Simulation Results for Crude Glycerine Column	153

Figure 65: Methanol Recovery.....	154
Figure 66: Selection of Optimum Reflux Ratio for Methanol Drying Column.....	155
Figure 67: Input Summary for 20-Tray Methanol Dryer ASPEN PLUS™ Simulation.....	156
Figure 68: Results of ASPEN PLUS™ Simulation for Methanol Dryer	157
Figure 69: Wastewater Treatment for Conversion of Soybean Oil to Biodiesel	158
Figure 70: Yield Analysis for Conversion of Soybean Oil to Biodiesel	159
Figure 71: Distribution of Steam Requirements for Conversion of Soybean Oil to Biodiesel (normalized per metric ton of biodiesel produced)	160
Figure 72: Ranking of Steam Requirements for Our Process Design Model and Reported Estimates for Commercial Technologies (kcal/metric ton of biodiesel)	162
Figure 73: Ranking of Electricity Requirements for Our Process Design Model and for Current Comparable Technology	163
Figure 74: Schematic of Inputs to TEAM™ Model for Conversion of Soybean Oil to Biodiesel	165
Figure 75: Biodiesel Transportation Modeling	168
Figure 76: Energy Economy for Biodiesel-Fueled Engines.....	179
Figure 77: Effect of Biodiesel Blend Level on NO _x Emissions for Four-Stroke Diesel Engines.....	182
Figure 78: Effect of Biodiesel Blend Level on PM10 Emissions for Four-Stroke Engines.....	182
Figure 79: Effect of Biodiesel Blend Level on CO Emissions for Four-Stroke Engines.....	183
Figure 80: Effect of Biodiesel Blend Level on NMHC for Four-Stroke Engines	183
Figure 81: Correlation for Soot Content in PM as a Function of Oxygen Content	186
Figure 82: Example of TEAM™ Interface	190
Figure 83. Map of the NERC regions in the United States and Canada	199
Figure 84: Nitrogen Fertilizer Modeling.....	200
Figure 85: Phosphorous Fertilizer Modeling.....	201
Figure 86: Potassium Fertilizer Modeling.....	202
Figure 87: Ranking of Primary Energy Demand for the Stages of Petroleum Diesel Production.....	209
Figure 88: Process Energy Demand for Petroleum Diesel Life Cycle.....	209
Figure 89: Transport Distances for Domestic and Foreign Crude Oil (kg-km).....	210
Figure 90: Primary Energy Demand of Advanced versus Conventional Crude Recovery	211
Figure 91: Process Energy Requirements of Advanced versus Crude Oil Extraction	211
Figure 92: Ranking of the Fossil Energy Demand for Stages of the Petroleum Diesel Life Cycle.....	212
Figure 93: Ranking of Primary Energy Demand for the Stages of Biodiesel Production.....	213
Figure 94: Process Energy Requirements for Biodiesel Life Cycle	214
Figure 95: Fossil Energy Requirements versus Fuel Product Energy for the Biodiesel Life Cycle	215
Figure 96: Carbon Dioxide Emissions for Petroleum Diesel Life Cycle	217

Figure 97: Biomass Carbon Balance for Biodiesel Life Cycle.....	218
Figure 98: Comparison of CO ₂ Emissions for Domestic and Foreign Crude Production.....	219
Figure 99: CO ₂ Emissions for Biodiesel Life Cycle.....	220
Figure 100: Comparison of Net CO ₂ Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends (g CO ₂ /bhp-h)	221
Figure 101: Effect of Biodiesel Blend Level on CO ₂ Emissions.....	222
Figure 102: Life Cycle Consumption of Coal and Natural Gas for Petroleum Diesel.....	223
Figure 103: Life Cycle Consumption of Uranium for Petroleum Diesel	224
Figure 104: Life Cycle Consumption of Limestone for Petroleum Diesel	225
Figure 105: Life Cycle Consumption of Water for Petroleum Diesel	225
Figure 106: Life Cycle Consumption of Coal and Oil for Biodiesel	226
Figure 107: Life Cycle Consumption of Natural Gas for Biodiesel	227
Figure 108: Life Cycle Consumption of Uranium for Biodiesel.....	228
Figure 109: Life Cycle Consumption of Limestone for Biodiesel	229
Figure 110: Petroleum Consumption for Petroleum Diesel, B20, and B100	229
Figure 111: Coal and Natural Gas Consumption for Petroleum Diesel, B20, and B100	230
Figure 112: Water Use for Petroleum Diesel, B20, and B100	230
Figure 113: THC Emissions from Petroleum Diesel Life Cycle	233
Figure 114: CH ₄ Emissions from Petroleum Diesel Life Cycle	234
Figure 115: CO Emissions for Petroleum Diesel Life Cycle	234
Figure 116: CO Emissions from the Petroleum Life Cycle (Excluding End-Use Combustion of the Fuel)	235
Figure 117: TPM Emissions from Petroleum Diesel Life Cycle.....	236
Figure 118: SO _x Emissions from Petroleum Diesel Life Cycle.....	236
Figure 119: NO _x Emissions from Petroleum Diesel Life Cycle (Reported as NO ₂).....	237
Figure 120: NO _x Emissions from Petroleum Diesel Life Cycle Excluding End-use Combustion (Reported as NO ₂).....	238
Figure 121: Life Cycle Emissions of HCl for Petroleum Diesel	238
Figure 122: Life Cycle Emissions of HF for Petroleum Diesel.....	239
Figure 123: THC Emissions from Biodiesel Life Cycle	241
Figure 124: Sources of THC and CH ₄ in Soybean Crushing	242
Figure 125: Sources of THC and CH ₄ in Soybean Agriculture.....	242
Figure 126: CH ₄ Emissions from the Biodiesel Life Cycle.....	243
Figure 127: Sources of CH ₄ Emissions from the Biodiesel Production Step	243
Figure 128: CO Emissions from the Biodiesel Life Cycle.....	244
Figure 129: CO Emissions from the Biodiesel Life Cycle (Excluding End-use).....	244

Figure 130: TPM Emissions from Biodiesel LCA	245
Figure 131: Sources of TPM in Soybean Agriculture.....	245
Figure 132: SO _x Emissions from Biodiesel Life Cycle (Reported as SO ₂).....	246
Figure 133: Sources of SO _x Emissions from Soy Oil Conversion Step.....	247
Figure 134: Source of SO _x from Soybean Crushing.....	247
Figure 135: Sources of SO _x Emissions from Soybean Agriculture	248
Figure 136: NO _x Emissions from Biodiesel Life Cycle.....	248
Figure 137: HCl Emissions from Biodiesel Life Cycle	249
Figure 138: HF Emissions from Biodiesel Life Cycle.....	249
Figure 139: Sources of HCl and HF in Soybean Crushing	250
Figure 140: Sources of HCl and HF in Soy Oil Conversion	250
Figure 141: Life Cycle Emissions of THC for Petroleum Diesel, B20, and B100.....	252
Figure 142: Life Cycle Emissions of CH ₄ for Petroleum Diesel, B20, and B100.....	252
Figure 143: Life Cycle Emissions of CO for Petroleum Diesel, B20, and B100	253
Figure 144: Life Cycle Particulate Matter Emissions for Petroleum Diesel, B20, and B100	253
Figure 145: Life Cycle SO _x Emissions for Petroleum Diesel, B20, and B100.....	254
Figure 146: Life Cycle NO _x Emissions for Petroleum Diesel, B20, and B100.....	254
Figure 147: Life Cycle HF Emissions for Petroleum Diesel, B20, and B100.....	255
Figure 148: Life Cycle HCl Emissions for Petroleum Diesel, B20, and B100	255
Figure 149: Effect of Biodiesel Blend on Life Cycle Air Emissions of CH ₄ , SO _x , HF, PM10, and CO ..	256
Figure 150: Effect of Biodiesel Blend Level on Air Emissions of NO _x , NMHC and HCl	257
Figure 151: Tailpipe Emissions of CO and NO _x for Petroleum Diesel and Biodiesel.....	260
Figure 152: Tailpipe Emissions of PM10, NMHC and SO _x for Petroleum Diesel and Biodiesel.....	260
Figure 153: Effect of Biodiesel on Tailpipe Emissions of Soot	261
Figure 154: Wastewater Flows for Petroleum Diesel Life Cycle.....	262
Figure 155: Wastewater Flows for Biodiesel Life Cycle	262
Figure 156: Comparison of Life Cycle Wastewater Flows for Petroleum Diesel and Biodiesel Life Cycles	263
Figure 157: Life Cycle Emissions of Solid Hazardous Waste for Petroleum Diesel.....	264
Figure 158: Life Cycle Flows of Nonhazardous Waste for Petroleum Diesel	264
Figure 159: Life Cycle Flows of Hazardous Solid Waste for Biodiesel	265
Figure 160: Life Cycle Flows of Nonhazardous Solid Waste for Biodiesel	265
Figure 161: Sources of Hazardous Waste in Soybean Agriculture.....	266
Figure 162: Hazardous Waste Generation for Petroleum Diesel, B20, and B100 Life Cycles	266
Figure 163: Nonhazardous Waste Generation for Petroleum Diesel, B20, and B100 Life Cycles	267

Figure 164: The Effect of an Ideal Location for Biodiesel on Life Cycle Consumption of Primary Energy Resources	269
Figure 165: Sources of Energy Savings in the Chicago Area Biodiesel Scenario.....	270
Figure 166 : Reductions in Life Cycle Air Emissions for the Chicago Area Biodiesel Scenario	271
Figure 167: Water and Solid Waste Emissions Reductions for the Chicago Area Biodiesel Scenario	272
Figure 168: The Effect of Conversion Energy Requirements on Primary Energy Resource Demands for Biodiesel.....	273
Figure 169: The Effect of Soybean Oil Conversion Energy Demands on Air Emissions for Biodiesel...	275
Figure 170: The Effect of Soybean Oil Conversion Energy Demands on Water and Solid Waste Emissions for Biodiesel.....	276

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1 How To Use This Report

Reporting on the results of a life cycle study is at best an awkward process. The complexity of such a study can lead to the necessary, but sometimes tedious, reporting of much detail. For life cycle analysis, the devil is truly in the details.

We recognize, however, that there are many types of readers who may find an interest in the results of our work. Therefore, we have presented our study at three different levels of detail: one for the policymaker interested in “cutting to the quick,” one for the more technically oriented staff often supporting policy decisions, and one for the “hard core” life cycle practitioner. This approach has undoubtedly led to some redundancy in our presentation. We apologize for any inconvenience that this may cause, but hope that (at least for those who bothered to stop here first before diving into the report) most will find this approach more economical in targeting the appropriate level of detail needed.

Here is a road map for finding your way around this report:

For a quick and concise description of the study and its results, see...

- Executive Summary (starting on page iii)

For the 2nd level of detail providing more information on how we conducted the study and a more detailed discussion of results, see...

- Section 1.0 Technical Overview. This overview is can be read without any need to reference later sections (including the bibliography at the end).

For the “hard core” details of our modeling and a detailed discussion of the results see...

- Section 2.0 through Section 11.0. The reader can start from section 2.0 to get a complete and detailed description of the study.

Each of the three levels described above is essentially free standing and can be read independently to get a full perspective on the study.

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2 Technical Overview

This report presents the findings from a study of the life cycle inventories (LCIs) for petroleum diesel and biodiesel. An LCI is a comprehensive quantification of all the energy and environmental flows associated with a product from “cradle to grave.” It provides information on:

- Raw materials extracted from the environment
- Energy resources consumed
- Air, water, and solid waste emissions generated.

By “cradle to grave,” we mean all the steps from the first extraction of raw materials from the environment to the final end-use of the product. LCIs are invaluable tools for assessing and comparing the overall environmental impacts of various products. One purpose for conducting this study is to assess overall greenhouse gas emissions from these two fuels. Because of the global nature of greenhouse gas effects, these emissions lend themselves very well to life cycle assessment (LCA). We also considered other environmental emissions; particularly regulated air emissions such as carbon monoxide, hydrocarbons, nitrogen oxides, sulfur oxides and particulate matter. The purpose of this study is to provide LCI data that can be used by industry and government decision-makers considering biodiesel as an alternative fuel. This study is the product of a highly effective partnership between the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE), which has brought together the agricultural and energy expertise needed to adequately address an LCI of biodiesel.

2.1 Stakeholder Involvement

Any good life cycle study makes use of every opportunity to obtain input from all who have a stake in the final outcome. This is especially true for those life cycle studies being conducted to support important government policy decisions. Many of the early decisions made in setting the scope of the study (see section 2.2) can have a profound effect on the outcome of the study. This makes it crucial that all stakeholders have an opportunity to discuss the key assumptions and options for the analysis. But stakeholder involvement cannot stop there. Input throughout the major steps of the project is useful for ensuring the proper use and interpretation of the best available data. Finally, as results from the LCI model become available, offering the opportunity to have stakeholders provide their perspective helps to avoid “tunnel vision.” The most important reason for stakeholder involvement in the study is *credibility*. When such studies are done in a vacuum, they stand little chance of getting buy-in from the industries involved. In the end, LCI results are only as good as the “buy-in” or level of credibility they engender.

We made stakeholder involvement a top priority in our study. The following is a list of the groups that provided input to us during the project:

- Petroleum Industry
- Oilseed Processing Industry
- Animal Renderers and Recyclers
- Chemical Process Industry

- Biodiesel Producers
- Engine Manufacturers
- U.S. Department of Agriculture
- U.S. Department of Energy
- U.S. Environmental Protection Agency
- State and Local Governments
- Environmental Public Interest Groups.

Outlined below is a brief description of the process used to continually check in with stakeholders. Throughout this process, we provided opportunities to communicate with us in writing, by phone, and by e-mail, as well as in our face-to-face meetings.

1. Before pen was put to paper, USDA and DOE brought together a consortium of stakeholders at a meeting hosted by USDA in Washington, DC, to discuss the need and goals of our study.
2. Based on input from this group, a preliminary scoping document was put together and distributed for review.
3. A second face-to-face meeting with stakeholders was held to work out the details of the project scope.
4. Once the basic data had been collected on all aspects of the petroleum diesel and biodiesel life cycles, the stakeholders reconvened to review the data. Feedback from this meeting resulted in our updating data sources and filling in gaps in available data.
5. Finally, once results from the LCI model were available, we sought detailed comments from a representative group of stakeholders (that is, those willing to put in the time to study our results). They were given a first draft of this report. Their comments have been carefully compiled. Wherever possible, we have made changes to the model and the report to reflect concerns and criticisms raised by this group. This document is a product of that final review.

The quality of our results is much the better for the input of these groups. We are indebted to the individuals who took the time to participate in this process.

2.2 Scope of the Life Cycle Study

2.2.1 Purpose

The purpose of this study is to conduct an LCI to quantify and compare the comprehensive sets of environmental flows (to and from the environment) associated with both biodiesel and petroleum-based diesel, over their entire life cycles. In addition to the purpose stated, this LCA was initiated to provide the necessary information that could be used to answer the following questions that have been posed by policy makers:

2.2.2 What Is “Biodiesel?”

In its most general sense, “biodiesel” has been used to refer to any diesel fuel substitute that is derived from renewable biomass. In the past few years, biodiesel has taken on a more specific definition and currently refers to a family of products made from vegetable oils or animal fats and alcohol, such as methanol or ethanol. These are called alkyl esters of fatty acids. In order for these alkyl esters of fatty acids to be considered as viable transportation fuels, they must meet stringent quality standards, otherwise they become standard industrial chemicals that are not suitable for diesel applications. Thus, alkyl esters

of fatty acids that meet transportation fuel standards are called “biodiesel.” One popular process for producing biodiesel is known as “transesterification.” This is the technology modeled in this report.

Today, biodiesel is made from a variety of natural oils. Chief among these are soybean oil and rapeseed oil. Rapeseed oil, a close cousin of canola oil, dominates the growing biodiesel industry in Europe. In the United States, biodiesel is being made from soybean oil because more soybean oil is produced than all other sources of fats and oil combined. There are many candidates for feedstocks, including recycled cooking oils, animal fats, and a variety of other oilseed crops. We selected soybean oil as the feedstock used for biodiesel production because of the vast number of data that have been generated about biodiesel from soybean oil.

Today, the most widely used alcohol for biodiesel production is methanol, mostly because of its ease of processing and its relatively low cost. We have chosen to model biodiesel production using methanol. Thus, the working definition of biodiesel in our study is a diesel fuel substitute made via the transesterification of soybean oil with methanol. In industry parlance, this biodiesel product is referred to as soy methyl ester or methyl soyate.

2.2.3 What Is “Petroleum Diesel?”

We defined petroleum diesel as “on-highway” low-sulfur diesel made from crude oil. Recent regulations promulgated by the U.S. Environmental Protection Agency (EPA) as part of its enforcement of the 1990 Clean Air Act Amendments set tougher restrictions on diesel used on the road versus diesel used off the road. The “on highway” diesel must now meet new limits for sulfur content that are an order of magnitude lower than previously allowed (0.05 wt% versus 0.5% sulfur). We restrict our evaluation of petroleum diesel to this new low-sulfur diesel².

2.2.4 Defining the Product Application

The choice of the fuels’ end-use can greatly affect the life cycle flows. Potential markets for biodiesel cover a wide range of diesel applications, including most truck operations, stationary generation, mining equipment, marine diesel engines, and bus fleets. In this study, we compare the use of petroleum diesel and biodiesel in urban buses. This choice was based on the availability of end-use data. The urban bus market was identified by the nascent U.S. biodiesel industry early on as a near-term opportunity, and a large number of data are available on the performance of diesel bus engines.

2.2.5 What Is Included in the Life Cycle Systems?

Major operations included within the boundary of the petroleum diesel system are:

- Extraction of crude oil from the ground
- Transport of crude oil to an oil refinery
- Refining of crude oil to diesel fuel
- Transport of diesel fuel to its point of use
- Use of the fuel in a diesel bus engine.

² One important clarification should be made about our characterization of petroleum diesel. In our analysis, low-sulfur diesel fuel is used in the product application (urban buses). This is not true for agricultural use of diesel fuel in the production of soybeans. Data for “off highway” diesel-powered tractors were used to characterize performance and emissions of these engines. This off-highway diesel is not held to the same strict standard for sulfur content.

For the biodiesel system, major operations include:

- Produce soybeans
- Transport soybeans to a soy crushing facility
- Recover soybean oil at the crusher
- Transport soybean oil to a biodiesel manufacturing facility
- Conversion of soybean oil to biodiesel
- Transport biodiesel fuel to the point of use
- Use the fuel in a diesel bus engine.
- These operations are not a comprehensive list of what has been modeled in our analysis. These operations include within them detailed processes described elsewhere in this report. For example, extraction of crude oil includes flows from a number of operations such as onshore and offshore drilling and natural gas separation. Onshore drilling is further characterized as either conventional or advanced technology.

We include more than just the energy and environmental flows that occur directly in each of these steps. Energy and environmental inputs from the production of any raw materials used in each step are also included. Generally, life cycle flows are characterized for all raw materials from the point of extracting their primary components from the environment. For example, methanol use in the biodiesel manufacturing facility contributes life cycle flows that go back to the extraction of natural gas used as a feedstock. Likewise, life cycle flows from intermediate energy sources such as electricity are included—back to extraction of coal, oil, natural gas, limestone, and any other primary resources needed.

2.2.6 What Are the Geographical Boundaries?

The LCA is limited to the use of petroleum diesel and biodiesel in the United States. This does not mean that all the steps involved in the life cycles are restricted to domestic boundaries. Petroleum diesel's life cycle, in particular, expands its geographic limits to include foreign crude oil production simply because half the crude oil used in the United States is imported. Other aspects of the geographic limits of the study involve the choice of national versus regional or even site-specific assessment. For domestic operations, we rely on national average data. For foreign operations, we rely on industry average data. Electricity generation is modeled on a national basis. Table 1 and Table 2 present specific information on the geographical scope of the analysis for each stage of the petroleum diesel and biodiesel life cycles.

2.2.7 What Is the Time Frame?

We were faced with two basic options: 1) model technology and markets as they are today; and 2) model a futuristic scenario based on projected technology and markets. We chose to focus on a current time frame. Thus, we consider production and end-use technologies that are available today for both petroleum diesel and biodiesel. This approach ignores future advances in production efficiency and end-use engine technology. By limiting the analysis to the present, it is far more “grounded” and objective because it relies on documented data rather than on potentially optimistic projections. Results from this study provide a baseline for considering future scenarios.

2.2.8 Basis for Comparing the Life Cycles

Common sense suggests that any comparison of two fuel products must be done on the same basis. In the lexicon of LCA, two industrial systems are compared on the same “functional basis.” In other words, the fuels are compared based on identical services they provide. Once this shared function is defined, a unit

has to be chosen in order to compare the systems on the same quantitative basis. For example, a comparison of fuel life cycles for passenger vehicles might characterize all life cycle flows per mile of travel delivered by the vehicle.

The unit used to normalize all life cycle flows is known as the “functional unit.” For a more detailed discussion of the definition and protocols established for LCIs, refer to publications from the Society of Environmental Toxicology and Chemistry (SETAC)³ and EPA⁴. Medium- and heavy-duty diesel engines are typically evaluated on the basis of actual work delivered by the engine. This approach is used because of the variability (or even the irrelevance) of mileage among the various applications for diesel engines. Therefore, we have chosen to compare the life cycle flows of biodiesel and petroleum diesel on the basis of 1 brake horsepower-hour (bhp-h) of work delivered by the bus engine.

Table 1: Geographic Scope of the Petroleum Diesel Life Cycle

Life Cycle Stage	Geographic Scope
Crude Oil Extraction	International average based on the consumption of crude oil in the United States
Crude Oil Transportation	International average transportation distances to the United States
Crude Oil Refining	U.S. national average
Diesel Fuel Transportation	U.S. national average
Diesel Fuel Use	U.S. national average based on urban bus use

Table 2: Geographic Scope of the Biodiesel Life Cycle

Life Cycle Stage	Geographic Scope
Soybean Agriculture	Average based on data from the 14 key soybean-producing states
Soybean Transportation	U.S. national average
Soybean Crushing	U.S. national average based on modeling of a generic U.S. crushing facility
Soybean Oil Transport	U.S. national average
Soybean Oil Conversion	U.S. average based on modeling of a generic biodiesel facility
Biodiesel Transportation	U.S. national average
Biodiesel Fuel Use	U.S. national average based on urban bus use

³ SETAC, *A Technical Framework for Life-Cycle Assessments*, Society of Environmental Toxicology and Chemistry, Washington DC, 1991; SETAC, *Guidelines for Life-Cycle Assessment: A “Code of Practice,”* Society of Environmental Toxicology and Chemistry, Washington, DC, 1993; SETAC, *A Conceptual Framework for Life-Cycle Impact Assessment*, Society of Environmental Toxicology and Chemistry, Washington, DC, 1993; SETAC, *Life Cycle Assessment Data Quality: A Conceptual Framework*, Society of Environmental Toxicology and Chemistry, Washington, DC, 1994.

⁴ EPA: *Life Cycle Design Manual: Environmental Requirements and the Product System*, EPA/600/R-92/226, 1993; U.S. Environmental Protection Agency, *Life-Cycle Assessment: Inventory Guidelines and Principles*, EPA/600/R-92-245, 1993; U.S. Environmental Protection Agency, *Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis*, EPA/530-R-95-010, 1995.

2.3 Key Assumptions

The details of the assumptions and modeling steps of the life cycle are presented in subsequent sections of this report, although two general assumptions applied in the modeling should be highlighted. First, national average distances were used for transport of all feedstocks, intermediates, and products. The effect of this assumption was tested in a sensitivity analysis. Second, both fuels are assumed to be used in “current” diesel engines, defined as engines calibrated to meet 1994 EPA regulations for diesel exhaust when operated on low-sulfur petroleum diesel. Other assumptions worth noting include:

- Crude oil delivery from domestic and foreign sources are split almost evenly
- Best available refinery data for extant facilities were used to model a “generic” refinery
- Emissions from petroleum diesel are assumed to meet 1994 engine emissions standards.
- Biodiesel assumptions worth noting include:
 - Agriculture practices and yields are based on weighted averages for 14 soybean-producing states
 - Emissions are based on actual engine data for biodiesel emissions that are then modeled as changes in the oxygen content⁵ in the fuel
 - Energy efficiencies of biodiesel-fueled engines are identical to those of petroleum diesel-fueled engines⁶
 - Biomass-derived carbon dioxide (CO₂) in the fuel emissions is recycled in soybean production.

For details on the bases for these assumptions, refer to the sections describing each stage of the life cycles.

2.4 Findings

LCI results are presented for 100% biodiesel (known as “B100”), a 20% blend of biodiesel with petroleum diesel (known as “B20”), and petroleum diesel. These results include estimates of:

- Overall energy requirements
- CO₂ emissions
- Other regulated and non-regulated air emissions. Regulated pollutants include carbon monoxide (CO), particulate matter less than 10 microns in size (PM10), non-methane hydrocarbons (NMHC), and nitrogen oxides (NO_x). Non-regulated air emissions include methane (CH₄), formaldehyde, benzene, total hydrocarbons (THC), and total particulate matter (TPM).
- Water emissions
- Solid wastes.

These life cycle flows are presented for the base-case scenarios and for two sensitivity studies. The base case describes petroleum diesel and biodiesel life cycle flows for “national average” scenarios.

The purpose of conducting sensitivity studies on the life cycle of biodiesel was to establish the potential range for improvement in the fuel, as well as to establish the range of possible error associated with the

⁵ Diesel fuel contains no oxygen. The amount of oxygen is a measure of biodiesel content in the fuel. In addition, percent oxygen proves to be a good basis for predicting emissions.

⁶ This is substantiated with an analysis of engine performance data.

assumptions made in the model. The LCI assumes a “current” time frame—that is, we are looking at options for improvement of agriculture, soybean oil recovery, conversion technology, and engine technology within a short-term horizon. This sets realistic limitations on the assumptions used in the model.

In each life cycle step we considered the potential for near-term improvement. Two main areas were identified. First, we felt it was important to understand the impact of location on biodiesel production. This allows us to consider the benefits of the best agricultural productivity available in the United States and the shortest distances for transport of fuel and materials. This sets an upper bound on biodiesel benefits from the perspective of current agricultural practices and transportation logistics.

Second, we identified the conversion of soybean oil to biodiesel as an aspect of the life cycle that has significant impact on energy use and emissions and that has a broad range of efficiencies, depending on the commercial technology used. Our base case estimate of the energy requirements for soy oil conversion is based on a preliminary engineering design prepared for this study. The design was loosely based on data from an extant transesterification plant in Kansas City, Missouri. Our energy budget proved to be much lower than that reported for the facility in Kansas City. A review of the literature on recent transesterification technology revealed that our design estimate is at the high end of the range of recently published literature values. To deal with this disparity in energy estimates for conversion of soy oil to biodiesel, we decided to look at the range of reported energy budgets as a sensitivity study.

Changes in engine technology may also be an avenue for improving biodiesel on a life cycle basis. We opted to forego this area in our sensitivity analysis because of limited data. Thus, we present in this report the results of two sensitivity studies:

- The base case for B100 is compared with the LCI for an optimal biodiesel location (Chicago). The choice of an optimal location is based on an evaluation of regions with the most efficient production of soybeans, local concentration of soybean producers, and large end-use markets for urban buses.
- Results for a range of high and low energy demands for soybean conversion to biodiesel are compared to determine the impact of this stage of the biodiesel life cycle on overall emissions and energy flows. Low and high values for energy consumption were based on a survey of technical literature on the most recent technologies commercially available.

2.4.1 Results of the Base Case Study

The results provided here allow the reader to make a nominal comparison of biodiesel and petroleum diesel. By nominal, we mean that the LCIs calculated for each fuel reflect generic “national average” models. The only exception to this statement is soybean agriculture data, which are provided on a state-by-state basis for the 14 key soybean-producing states. Implicit in such a nominal comparison is that there are no regional differences that could affect any of the stages of each fuel’s life cycle. There will, of course, be differences that will affect each fuel.

In most cases, biodiesel is interchangeable with petroleum diesel without any need to modify today’s diesel engine. However, one key issue for biodiesel use that should be explicitly is the effect of regional climate on the performance of the fuel. This fuel’s cold flow properties may limit its use in certain parts of the country during the winter. This caveat should be kept in mind. Means of mitigating biodiesel’s cold flow properties are being evaluated by researchers, though no clear solution is at hand. Low-sulfur #2 diesel fuel has similar limitations that are currently addressed with the use of additives and by blending this fuel with #1 diesel fuel.

2.4.1.1 Life Cycle Energy Balance

LCIs provide an opportunity to quantify the total energy demands and the overall energy efficiencies of processes and products. Understanding the overall energy requirements of biodiesel is key to our understanding the extent to which biodiesel made from soybean oil is a “renewable energy” source. Put quite simply, the more fossil energy required to make a fuel, the less we can say that this fuel is “renewable”. Thus, the renewable nature of a fuel can vary across the spectrum of “completely renewable.” (i.e., no fossil energy input) to nonrenewable (i.e., fossil energy inputs as much or more than the energy output of the fuel)⁷. Energy efficiency estimates help us to determine how much additional energy must be expended to convert the energy available in raw materials used in the fuel’s life cycle to a useful transportation fuel. The following sections describe these basic concepts in more detail, as well as the results of our analysis of the life cycle energy balances for biodiesel and petroleum diesel.

2.4.1.1.1 Types of Life Cycle Energy Inputs

In this study, we track several types of energy flows through each fuel life cycle. For clarity, each of these energy flows is defined below.

- *Total Primary Energy.* All raw materials extracted from the environment can contain⁸ energy. In estimating the total primary energy inputs to each fuel’s life cycle, we consider the cumulative energy content of all resources extracted from the environment.
- *Feedstock Energy.* Energy contained in raw materials that end up directly in the final fuel product is termed “feedstock energy.” For biodiesel production, feedstock energy includes the energy contained in the soybean oil and methanol feedstocks that are converted to biodiesel. Likewise, the petroleum directly converted to diesel in a refinery contains primary energy that is considered a feedstock energy input for petroleum diesel. Feedstock energy is a subset of the primary energy inputs.
- *Process Energy.* The second major subset of primary energy is “process energy.” This is limited to energy inputs in the life cycle exclusive of the energy contained in the feedstock (as defined in the previous bullet). It is the energy contained in raw materials extracted from the environment that does not contribute to the energy of the fuel product itself, but is needed in the processing of feedstock energy into its final fuel product form. Process energy consists primarily of coal, natural gas, uranium, and hydroelectric power sources consumed directly or indirectly in the fuel’s life cycle.
- *Fossil Energy.* Because we are concerned about the renewable nature of biodiesel, we also track the primary energy that comes from fossil sources specifically (coal, oil, and natural gas). All three of the previously defined energy flows can be categorized as fossil or nonfossil energy.
- *Fuel Product Energy.* The energy contained in the final fuel product, which is available to do work in an engine, is what we refer to as the “fuel product energy”. All other things being equal, fuel product energy is a function of the energy density of each fuel.

⁷ This last statement is an oversimplification. We consider the energy trapped in soybean oil to be renewable because it is solar energy stored in liquid form through biological processes that are much more rapid than the geologic time frame associated with fossil energy formation. Also, other forms of nonrenewable energy besides fossil fuel exist.

⁸ The energy “contained” in a raw material is the amount of energy that would be released by the complete combustion of that raw material. This “heat of combustion” can be measured in two ways: as a higher heating value or a lower heating value. Combustion results in the formation of CO₂ and water. Higher heating values consider the amount of energy released when the final combustion products are gaseous CO₂ and liquid water. Lower heating values take into account the loss of energy associated with the vaporization of the liquid water combustion product. Our energy content is based on the lower heating values for each material.

2.4.1.1.2 Defining Energy Efficiency

We report two types of energy efficiency. The first is the overall “life cycle energy efficiency”. The second is what we refer to as the “fossil energy ratio”. Each elucidates a different aspect of the life cycle energy balance for the fuels studied.

The calculation of the life cycle energy efficiency is simply the ratio of fuel product energy to total primary energy:

$$\text{Life Cycle Energy Efficiency} = \text{Fuel Product Energy} / \text{Total Primary Energy}$$

It is a measure of the amount of energy that goes into a fuel cycle, which actually ends up in the fuel product. This efficiency accounts for losses of feedstock energy and additional process energy needed to make the fuel.

The fossil energy ratio tells us something about the degree to which a given fuel is or is not renewable. It is defined simply as the ratio of the final fuel product energy to the amount of fossil energy required to make the fuel:

$$\text{Fossil Energy Ratio} = \text{Fuel Energy} / \text{Fossil Energy Inputs}$$

If the fossil energy ratio has a value of zero, then a fuel is not only completely nonrenewable, but it provides no useable fuel product energy as a result of the fossil energy consumed to make the fuel. If the fossil energy ratio is equal to 1, then this fuel is still nonrenewable. A fossil energy ratio of one means that no loss of energy occurs in the process of converting the fossil energy to a useable fuel. For fossil energy ratios greater than 1, the fuel actually begins to provide a leveraging of the fossil energy required to make the fuel available for transportation. As a fuel approaches being “completely” renewable, its fossil energy ratio approaches “infinity.” In other words, a completely renewable fuel has no requirements for fossil energy.

From a policy perspective, these are important considerations. Policymakers want to understand the extent to which a fuel increases the renewability of our energy supply. Another implication of the fossil energy ratio is the question of climate change. Higher fossil energy ratios imply lower net CO₂ emissions. This is a secondary aspect of the ratio, as we are explicitly estimating total CO₂ emissions from each fuel’s life cycle. Nevertheless, the fossil energy ratio serves as a check on our calculation of CO₂ life cycle flows (since the two should be correlated).

2.4.1.1.3 Petroleum Diesel Life Cycle Energy Consumption

Table 3 and Figure 1 show the total primary energy requirements for the key steps in the production and use of petroleum diesel. The LCI model shows that 1.2007 MJ of primary energy is used to make 1 MJ of petroleum diesel fuel. This corresponds to a life cycle energy efficiency of 83.28%⁹.

The distribution of the primary energy requirements for each stage of the petroleum diesel life cycle is shown in Table 3. In Figure 1, the stages of petroleum diesel production are ranked from highest to lowest in terms of primary energy demand. Ninety-three percent of the primary energy demand is for extracting crude oil from the ground. About 88% of the energy shown for crude oil extraction is associated with the energy value of the crude oil itself. The crude oil refinery step for making diesel fuel dominates the remaining 7% of the primary energy use.

Removing the feedstock energy of the crude itself from the primary energy total allows us to analyze the relative contributions of the process energy used in each life cycle. Process energy used in each stage of the petroleum life cycle is shown in Figure 2. Process energy demand represents 20% of the energy

⁹ Using the total primary energy reported in Table 3, Life Cycle Energy Efficiency = 1 MJ of Fuel Product Energy / 1.2007 MJ of Primary Energy Input = 0.8328.

ultimately available in the petroleum diesel fuel product. About 90% of the total process energy is in refining (60%) and extraction (29%). The next largest contribution to total process energy is for transporting foreign crude oil to domestic petroleum refiners.

Table 3: Primary Energy Requirements for the Petroleum Diesel Life Cycle

Stage	Primary Energy (MJ per MJ of Fuel)	Percent
Domestic Crude Production	0.5731	47.73%
Foreign Crude Oil Production	0.5400	44.97%
Domestic Crude Transport	0.0033	0.28%
Foreign Crude Transport	0.0131	1.09%
Crude Oil Refining	0.0650	5.41%
Diesel Fuel Transport	0.0063	0.52%
Total	1.2007	100.00%

There are some significant implications in the process energy results shown in Figure 2 regarding trends for foreign and domestic crude oil production and use. Transportation of foreign crude oil carries with it a fourfold penalty for energy consumption compared to domestic petroleum transport because the overseas transport of foreign oil by tanker increases the travel distance for foreign oil by roughly a factor of four.

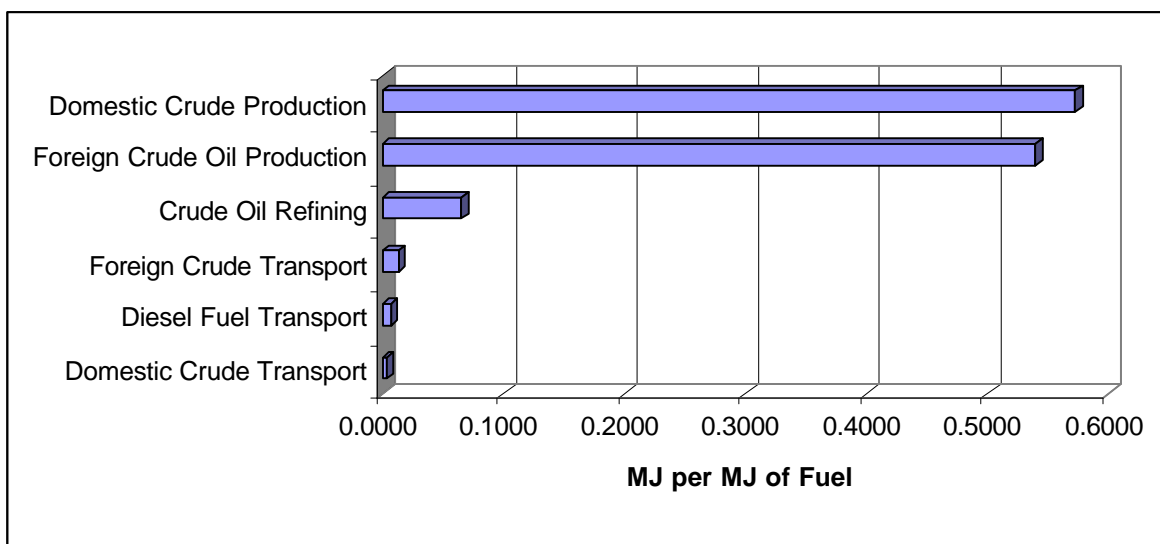


Figure 1: Ranking of Primary Energy Demand for the Stages of Petroleum Diesel Production

At the same time, domestic crude oil extraction is more energy intensive than foreign crude oil production. Advanced oil recovery practices in the United States represent 11% of the total production volume, compared to 3% for foreign oil extraction. Advanced oil recovery uses twice as much primary energy per kilogram of oil compared to conventional extraction. Per kilogram of oil out of the ground, advanced crude oil extraction requires almost 20 times more process energy than onshore domestic crude oil extraction because the processes employed are energy intensive and the amount of oil recovered is low

compared to other practices. Domestic crude oil supply is essentially equal to foreign oil supply (50.26% versus 49.74%, respectively) in our model, but its process energy requirement is 62% higher than that of foreign crude oil production (see Figure 2).

If our present trend of increased dependence on foreign oil continues, we can expect the life cycle energy efficiency of petroleum diesel to worsen because of the higher energy costs of transporting foreign crude to the United States. In addition, with declining domestic oil supplies, we may well see increased energy penalties for domestic crude oil extraction, as the practice of advanced oil recovery increases.

Table 4 and Figure 3 summarize the fossil energy inputs with respect to petroleum diesel's energy output. Petroleum diesel uses 1.1995 MJ of fossil energy to produce 1 MJ of fuel product energy. This corresponds to a fossil energy ratio of 0.8337¹⁰. Because the main feedstock for diesel production is itself a fossil fuel, it is not surprising that this ratio is almost identical to the life cycle energy efficiency of 83.28%. In fact, fossil energy associated with the crude oil feedstock accounts for 93% of the total fossil energy consumed in the life cycle. The fossil energy ratio is slightly less than the life cycle energy ratio because there is a very small contribution to the total primary energy demand, which is met through hydroelectric and nuclear power supplies related to electricity generation.

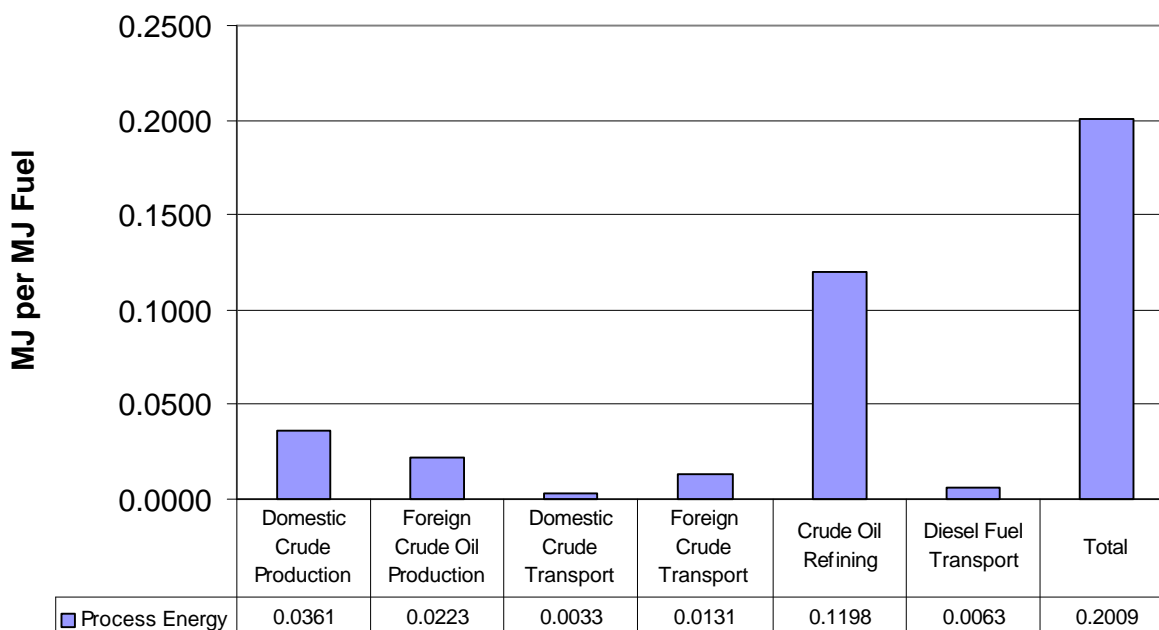


Figure 2: Process Energy Demand for Petroleum Diesel Life Cycle

2.4.1.1.4 Biodiesel Life Cycle Energy Demand

Table 5 and Figure 4 present the total primary energy demand used in each stage of the biodiesel life cycle. One MJ of biodiesel requires an input of 1.2414 MJ of primary energy, resulting in a life cycle energy efficiency of 80.55%. Biodiesel is comparable to petroleum diesel in the conversion of primary energy to fuel product energy (80.55% versus 83.28%). The largest contribution to primary energy (87%) is the soybean oil conversion step because this is where we have chosen to include the feedstock energy

¹⁰ Fossil Energy Ratio = 1 MJ Fuel Energy/1.1995 MJ of Fossil Energy Input = 0.8337.

associated with the soybean oil itself¹¹. As with the petroleum life cycle, the stages of the life cycle that are burdened with the feedstock energy overwhelm all other stages. Had the soybean oil energy been included with the farming operation, then soybean agriculture would have been the dominant consumer of primary energy. This is analogous to placing the crude oil feedstock energy in the extraction stage for petroleum diesel fuel. The next two largest primary energy demands are for soybean crushing and soybean oil conversion. They account for most of the remaining 13% of the total demand.

Table 4: Fossil Energy Requirements for the Petroleum Diesel Life Cycle

Stage	Fossil Energy (MJ per MJ of Fuel)	Percent
Domestic Crude Production	0.572809	47.75%
Foreign Crude Oil Production	0.539784	45.00%
Domestic Crude Transport	0.003235	0.27%
Foreign Crude Transport	0.013021	1.09%
Crude Oil Refining	0.064499	5.38%
Diesel Fuel Transport	0.006174	0.51%
Total	1.199522	100.00%

When we look at process energy separately from primary energy, we see that energy demands in the biodiesel life cycle are not dominated by soybean oil conversion (Figure 5). The soybean crushing and soy oil conversion to biodiesel demand the most process energy (34.25 and 34.55%, respectively, of the total demand). Agriculture accounts for most of the remaining process energy consumed in life cycle for biodiesel (almost 25% of total demand). Each transportation step is only 2%-3% of the process energy used in the life cycle.

¹¹ Energy contained in the soybean oil itself represents, in effect, the one place in the biodiesel life cycle where input of solar energy is accounted for. Total radiant energy available to soybean crops is essentially viewed as “free” in the life cycle calculations. It becomes an accountable element of the life cycle only after it has been incorporated in the soybean oil itself. This is analogous to counting the feedstock energy of crude petroleum as the point in its life cycle where solar energy input occurs. Petroleum is essentially stored solar energy. The difference between petroleum and soybean oil as sinks for solar energy is their time scale. While soybean oil traps solar energy on a rapid (“real time”) basis, petroleum storage represents a process that occurs on a geologic time scale. This difference in the dynamic nature of solar energy utilization is the key to our definitions of renewable and nonrenewable energy.

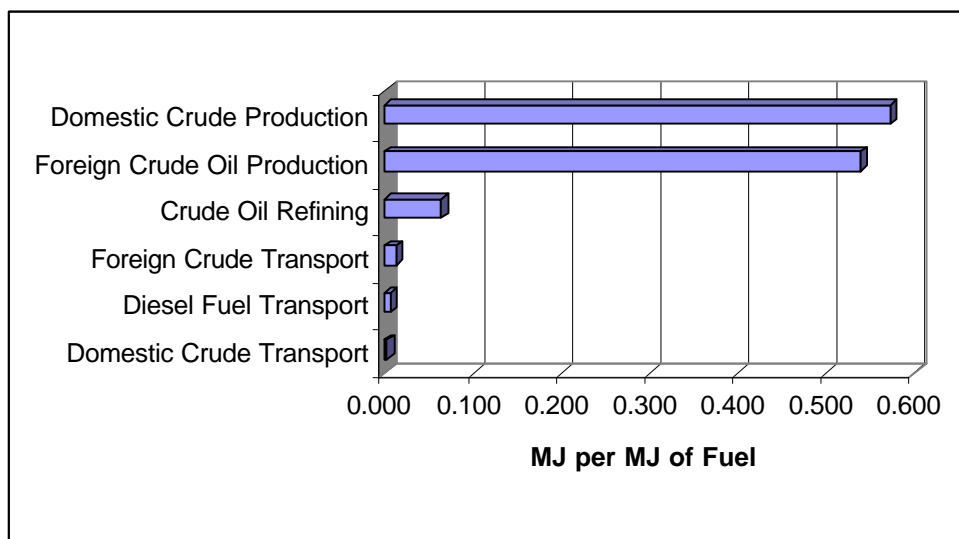


Figure 3: Ranking of Fossil Energy Demand for Stages of the Petroleum Diesel Life Cycle

Table 5: Primary Energy Requirements for Biodiesel Life Cycle

Stage	Primary Energy (MJ per MJ of Fuel)	Percent
Soybean Agriculture	0.0660	5.32%
Soybean Transport	0.0034	0.27%
Soybean Crushing	0.0803	6.47%
Soy Oil Transport	0.0072	0.58%
Soy Oil Conversion	1.0801	87.01%
Biodiesel Transport	0.0044	0.35%
Total	1.2414	100.00%

Table 6 and Figure 6 summarize the fossil energy requirements for the biodiesel life cycle. Because 90% of its feedstock requirements are renewable (that is, soybean oil), biodiesel's fossil energy ratio is favorable. Biodiesel uses 0.3110 MJ of fossil energy to produce one MJ of fuel product; this equates to a fossil energy ratio of 3.215. In other words, the biodiesel life cycle produces more than three times as much energy in its final fuel product as it uses in fossil energy. Fossil energy demand for the conversion step is almost twice that of its process energy demand, making this stage of the life cycle the largest contributor to fossil energy demand. The use of methanol as a feedstock in the production of biodiesel accounts for this high fossil energy demand. We have counted the feedstock energy of methanol coming into the life cycle at this point, assuming that the methanol is produced from natural gas. This points out an opportunity for further improvement of the fossil energy ratio by substituting natural gas-derived methanol with renewable sources of methanol, ethanol or other alcohols.

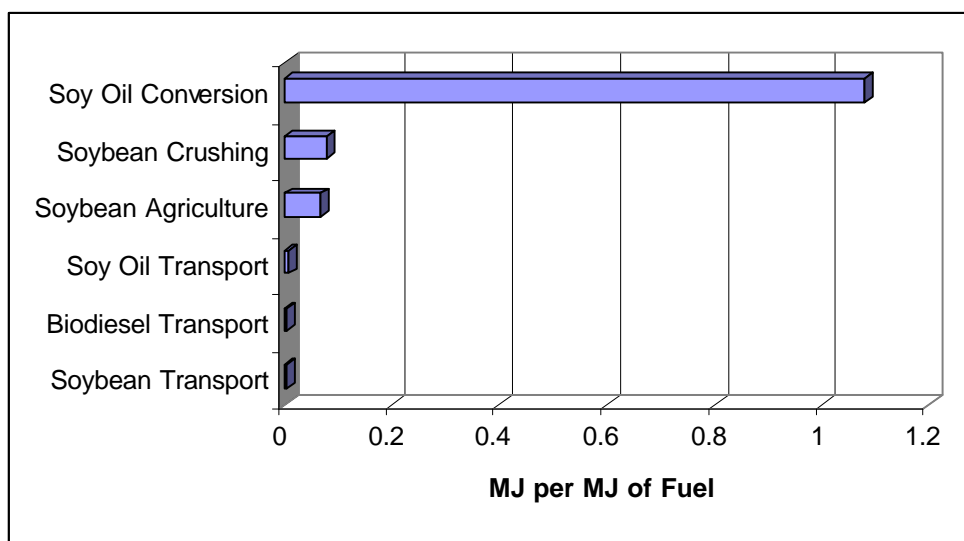


Figure 4: Ranking of Primary Energy Demand for Stages of the Biodiesel Life Cycle

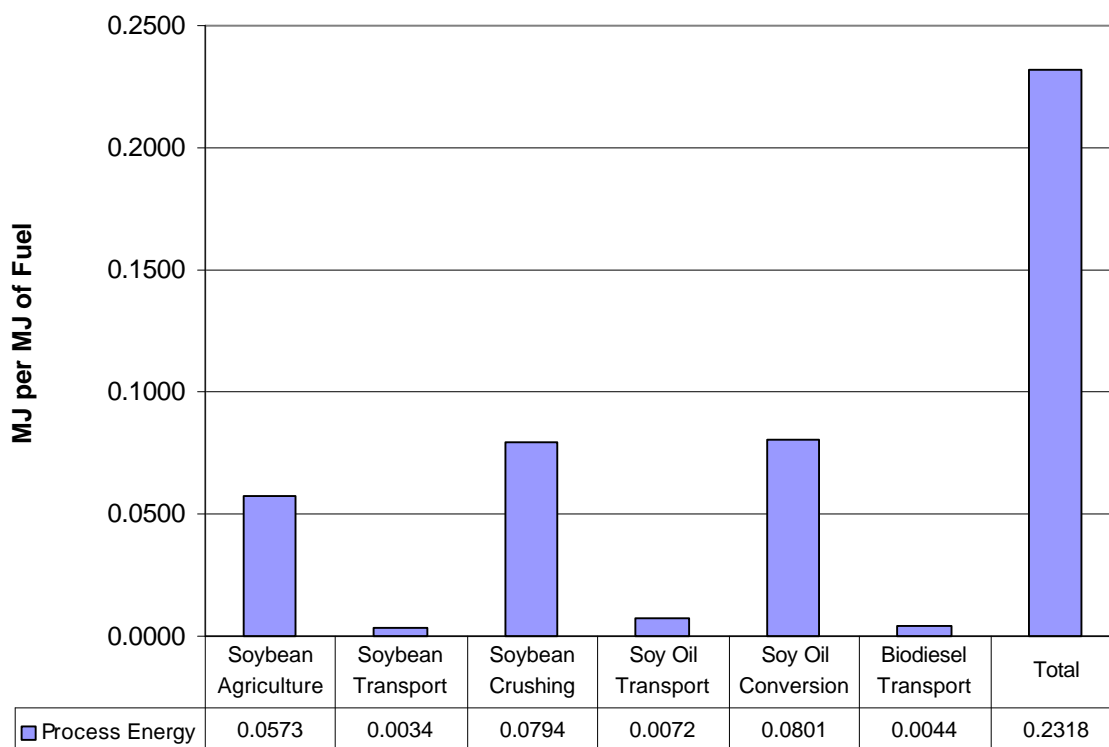


Figure 5: Process Energy Requirements for Biodiesel Life Cycle

Table 6: Fossil Energy Requirements for the Biodiesel Life Cycle

Stage	Fossil Energy (MJ per MJ of Fuel)	Percent
Soybean Agriculture	0.0656	21.08%
Soybean Transport	0.0034	1.09%
Soybean Crushing	0.0796	25.61%
Soy Oil Transport	0.0072	2.31%
Soy Oil Conversion	0.1508	48.49%
Biodiesel Transport	0.0044	1.41%
Total	0.3110	100.00%

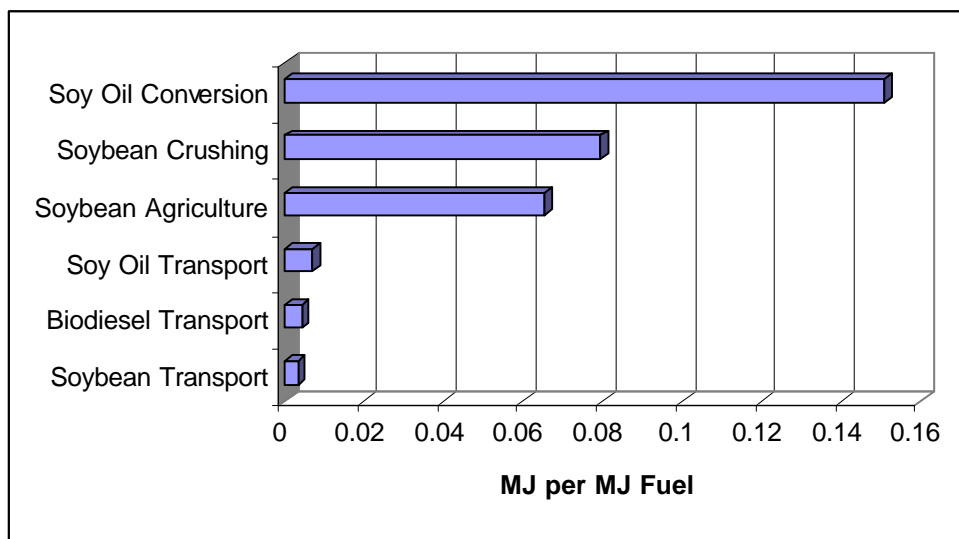


Figure 6: Fossil Energy Requirements versus Fuel Product Energy for the Biodiesel Life Cycle

2.4.1.1.5 Effect of Biodiesel on Life Cycle Energy Demands

Compared on the basis of primary energy inputs, biodiesel and petroleum diesel are essentially equivalent. Biodiesel has a life cycle energy efficiency of 80.55%, compared to 83.28% for petroleum diesel. The slightly lower efficiency reflects a slightly higher demand for process energy across the life of cycle for biodiesel. On the basis of fossil energy inputs, biodiesel enhances the effective use of this finite energy resource. Biodiesel leverages fossil energy inputs by more than three to one.

2.4.1.2 CO₂ Emissions

2.4.1.2.1 Accounting for Biomass-Derived Carbon

Biomass plays a unique role in the dynamics of carbon flow in our biosphere. Biological cycling of carbon occurs when plants (biomass such as soybean crops) convert atmospheric CO₂ to carbon-based compounds through photosynthesis. This carbon is eventually returned to the atmosphere as organisms consume the biological carbon compounds and respire. Biomass derived fuels reduce the net atmospheric carbon in two ways. First, they participate in the relatively rapid biological cycling of carbon to the atmosphere (via engine tailpipe emissions) and from the atmosphere (via photosynthesis). Second, these fuels displace the use of fossil fuels. Combustion of fossil fuels releases carbon that took millions of years to be removed from the atmosphere, while combustion of biomass fuels participates in a process that allows rapid recycle of CO₂ to fuel. The net effect of shifting from fossil fuels to biomass-derived fuels is, thus, to reduce the amount of CO₂ present in the atmosphere.

Because of the differences in the dynamics of fossil carbon flow and biomass carbon flow to and from the atmosphere, biomass carbon must be accounted for separately from fossil-derived carbon. The LCI model tracks carbon from the point at which it is taken up as biomass via photosynthesis to its final combustion as biodiesel used in an urban bus. The biomass-derived carbon that ends up as CO₂ leaving the tailpipe of the bus is subtracted from the total CO₂ emitted by the bus because it is ultimately reused in the production of new soybean oil. In order to ensure that we accurately credit the biodiesel LCI for the amount of recycled CO₂, we provide a material balance on biomass carbon.

The material balance shows all the biomass carbon flows associated with the delivery of 1 bhp-h of engine work (Figure 7). For illustration purposes, only the case of 100% biodiesel is shown. Lower blend rates proportionately lower the amount of biomass carbon credited as part of the recycled CO₂. Carbon incorporated in the meal fraction of the soybeans is not included in the carbon balance. Only carbon in the fatty acids and triglycerides that are used in biodiesel production are tracked. Not all the carbon incorporated in fatty acids and triglycerides ends up as CO₂ after combustion of biodiesel. Some oil loss occurs in the meal by-product. Glycerol is removed from the triglycerides as a by-product. Fatty acids are removed as soaps and waste. Finally, carbon released in combustion ends up in the form of CO₂, CO, THC, and TPM. Of the 169.34 grams of carbon absorbed in the soybean agriculture stage, only 148.39 grams (87%) end up in biodiesel. After accounting for carbon that ends up in other combustion products, 148.05 grams of carbon end up as 543.34 grams of tailpipe CO₂. This CO₂ is subtracted from the diesel engine emissions as part of the biological recycle of carbon. No credit is taken for the 13% of the carbon that ends up in various by-products and waste streams.

2.4.1.2.2 Comparison of CO₂ Emissions for Biodiesel and Petroleum Diesel

Table 7 summarizes CO₂ flows from the total life cycles of biodiesel and petroleum diesel and the total CO₂ released at the tailpipe for each fuel. The dominant sources of CO₂ for both the petroleum diesel life cycle and the biodiesel life cycle is the combustion of fuel in the bus. For petroleum diesel, CO₂ emitted from the tailpipe of the bus represents 86.54% of the total CO₂ emitted across the entire life cycle of the fuel. Most remaining CO₂ comes from emissions at the oil refinery, which contributes 9.6% of the total CO₂ emissions. For biodiesel, 84.43% of the CO₂ emissions occur at the tailpipe. The remaining CO₂ comes almost equally from soybean agriculture, soybean crushing, and conversion of soy oil to biodiesel.

At the tailpipe, biodiesel emits 4.7% more CO₂ than petroleum diesel, most of which is renewable. The nonrenewable portion comes from the methanol. Biodiesel generates 573.96 g/bhp-h compared with 548.02 g/bhp-h for petroleum diesel. The higher CO₂ levels result from more complete combustion and the concomitant reductions in other carbon-containing tailpipe emissions. As Figure 8 shows, the overall life cycle emissions of CO₂ from B100 are 78.45% lower than those of petroleum diesel. The reduction is

a direct result of carbon recycling in soybean plants. B20, the most commonly used form of biodiesel in the US, reduces net CO₂ emissions by 15.66% per gallon of fuel used.

Table 7: Tailpipe Contribution to Total Life Cycle CO₂ for Petroleum Diesel and Biodiesel (g CO₂/bhp-h)

Fuel	Total Life Cycle Fossil CO ₂	Total Life Cycle Biomass CO ₂	Total Life Cycle CO ₂	Tailpipe Fossil CO ₂	Tailpipe Biomass CO ₂	Total Tailpipe CO ₂	% of Total CO ₂ from Tailpipe
Petroleum Diesel	633.28	0.00	633.28	548.02	0.00	548.02	86.54%
B100	136.45	543.34	679.78	30.62	543.34	573.96	84.43%

2.4.1.3 Primary Resource Consumption for Biodiesel and Petroleum Diesel

The use of B100 as a substitute for petroleum diesel effects a 95% reduction in life cycle consumption of petroleum. Figure 9 compares petroleum oil consumption for petroleum diesel, B20, and B100. The 20% blend of biodiesel provides a proportionate reduction of 19%.

Consumption of coal and natural gas is a different story (Figure 10). The use of B100 increases life cycle consumption of coal by 19%. This reflects the higher overall demand for electricity in the biodiesel life cycle, relative to petroleum diesel. Electricity demand for soybean crushing is the dominant factor in electricity consumption for biodiesel because of the mechanical processing and solids handling equipment involved in this step. Life cycle consumption of natural gas increases by 77% for biodiesel versus petroleum diesel. Two factors contribute to this increase: 1) the assumed use of natural gas for the supply of steam and process heat in soybean crushing and soy oil conversion, and 2) the use of natural gas to produce methanol used in the conversion step.

The biodiesel life cycle imposes a higher burden on water resources than the petroleum diesel life cycle. Water use for petroleum diesel is not even visible on a plot scaled to show biodiesel use (Figure 11). That is because the biodiesel life cycle uses water at a rate that is three orders of magnitude higher than that of petroleum diesel. The impact of this water use is not addressed in this report. We offer no simple way to compare water use between the two life cycles because there is no simple equivalency in its use and final disposition.

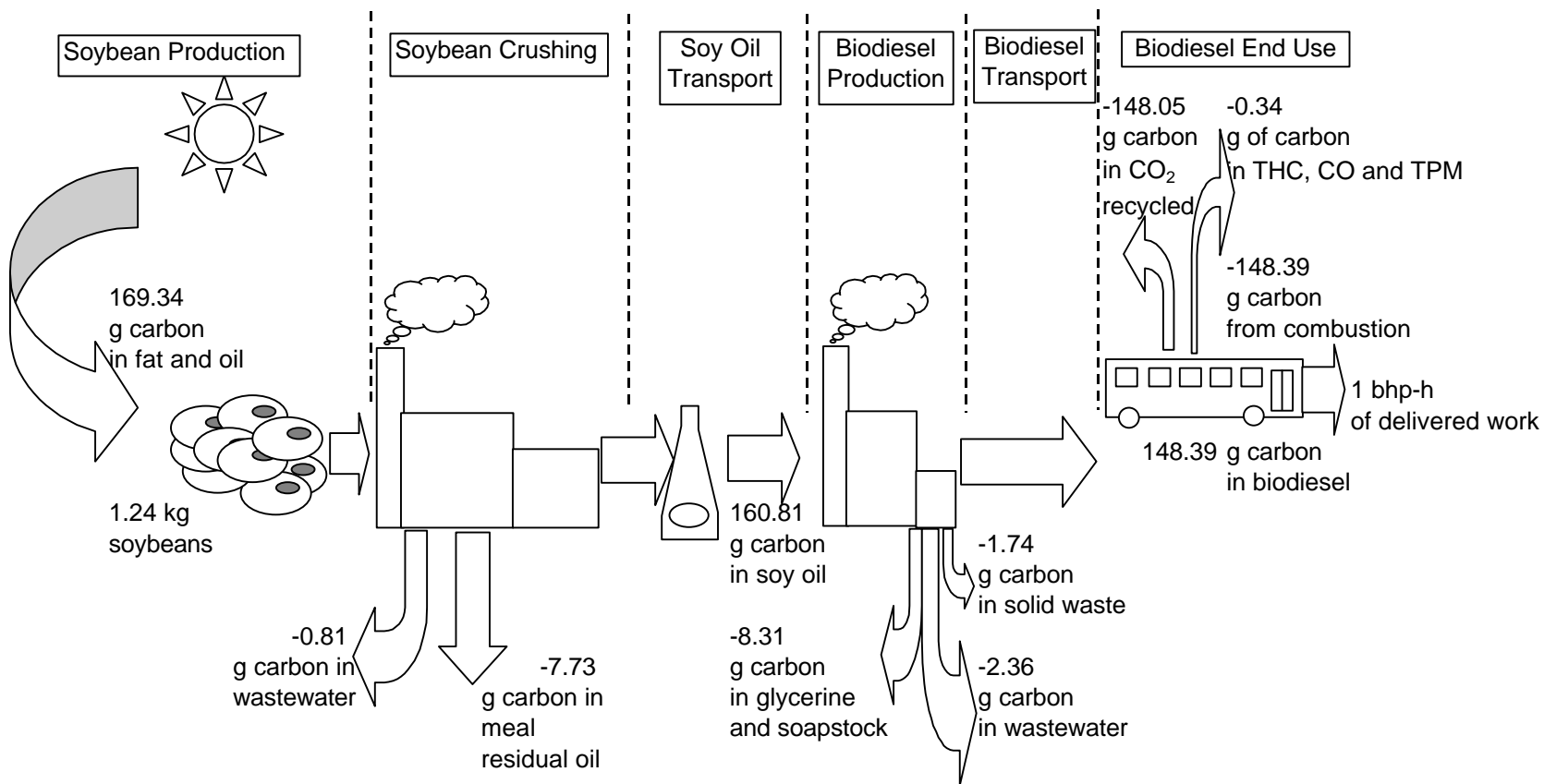


Figure 7: Biomass Carbon Balance for Biodiesel Life Cycle (g carbon/bhp-h)¹²

¹² All numbers presented as carbon equivalent. To calculate actual CO₂ emissions, multiply carbon equivalent numbers by 3.67 (the ratio of the molecular weight of CO₂ divided by the molecular weight of carbon).

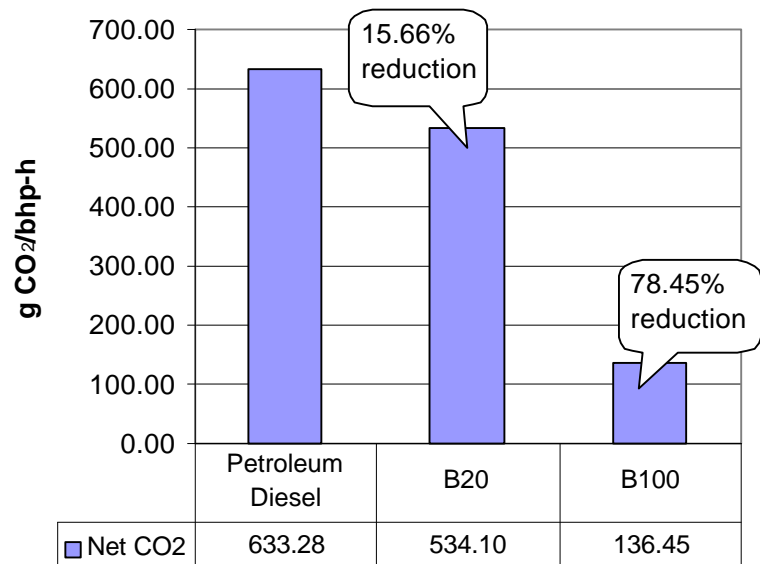


Figure 8: Comparison of Net CO₂ Life Cycle Emissions for Petroleum Diesel and Biodiesel Blends¹³

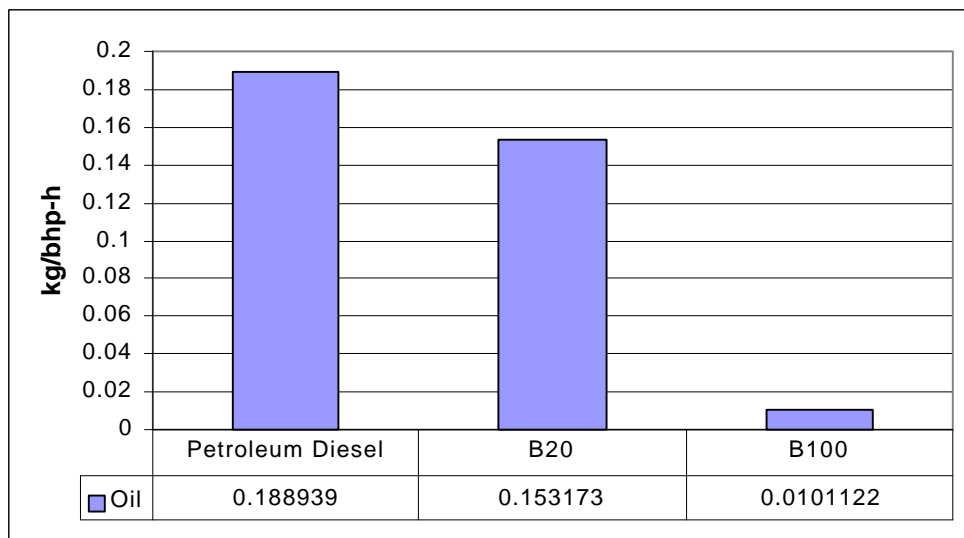


Figure 9: Petroleum Consumption for Petroleum Diesel, B20, and B100

¹³ Net CO₂ calculated by setting biomass CO₂ emissions from the tailpipe to zero.

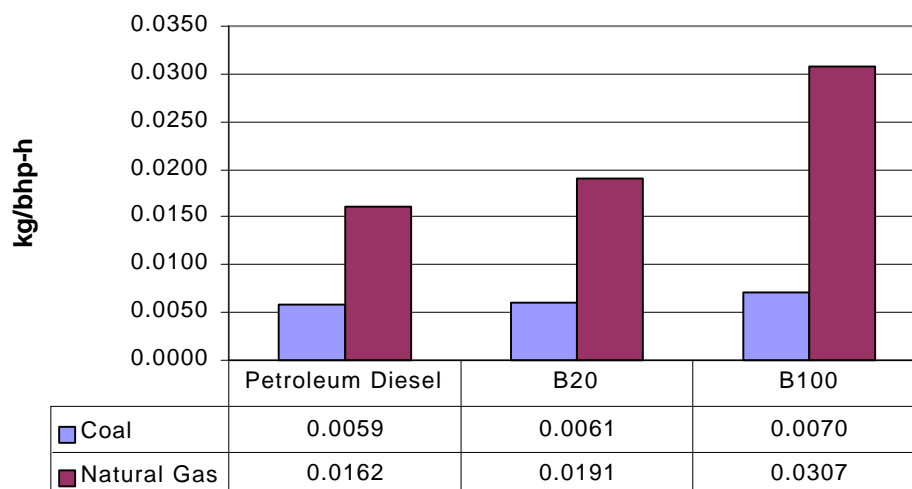


Figure 10: Coal and Natural Gas Consumption for Petroleum Diesel, B20, and B100

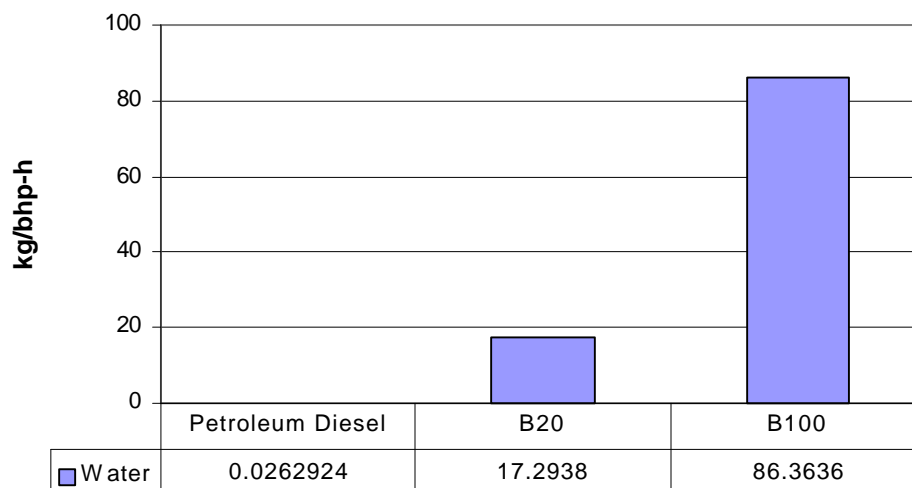


Figure 11: Water Use for Petroleum Diesel, B20, and B100

2.4.1.4 Life Cycle Emissions of Regulated and Nonregulated Air Pollutants

Regulated air pollutants include the following:

- Carbon Monoxide (CO)
- Nitrogen Oxides (NO_x)
- Particulate Matter Less Than 10 Microns (PM10)
- Sulfur Oxides (SO_x)
- Non Methane Hydrocarbons (NMHC)

The emissions of these air pollutants are regulated at the tailpipe for diesel engines. Sulfur dioxide (SO_x) does not have specific tailpipe limits, but it is controlled through sulfur content of the fuel. Other air emissions included in this study are methane (CH₄), benzene, formaldehyde, nitrous oxide (N₂O), hydrochloric acid (HCl), hydrofluoric acid (HF), and ammonia. N₂O is associated with agricultural field emissions. HCl and HF are associated with coal combustion in electric power stations. Ammonia is released primarily during fertilizer production.

2.4.1.4.1 Comparison of Life Cycle Air Emissions for Biodiesel and Petroleum Diesel

Figure 12 summarizes the differences in life cycle air emissions for B100 and B20 versus petroleum diesel fuel. In this section, we discuss overall differences in the emissions of the biodiesel and petroleum life cycles. More detail on the sources of the differences is presented in section 9.1.4 Life Cycle Emissions of Regulated and Nonregulated Air Pollutants.

We report particulate matter and hydrocarbons differently from the definitions used by EPA in their regulations. This difference in reporting is due to variations in how different data sources for the stages of the life cycle report these emissions. Benzene and formaldehyde emissions are not consistently reported. Some sources explicitly define emissions for non-methane hydrocarbons (NMHC), while others do not specify this distinction. Hydrocarbon data are reported as THC, defined as:

$$THC = (CH_4 + Benzene + formaldehyde + HC_{unspecified} + HC_{noCH_4})$$

where:

THC = total hydrocarbons

CH₄ = methane

HC_{unspecified} = unspecified hydrocarbons

HC_{noCH₄} = hydrocarbons excluding methane

Likewise, particulates are combined as a single category according to the following formula:

$$TPM = (PM_{10} + PM_{unspecified})$$

where:

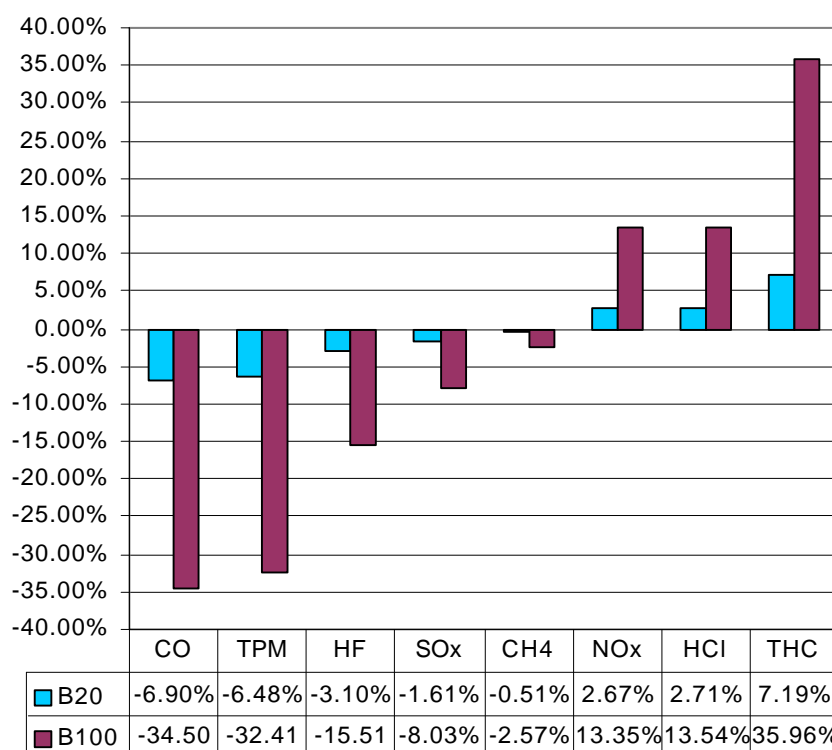
TPM = total particulate matter

PM₁₀ = particulate matter less than 10 micron

PM_{unspecified} = unspecified particulate matter

The replacement of petroleum diesel with biodiesel in an urban bus reduces life cycle air emissions for all but three of the pollutants we tracked. The largest reduction in air emissions that occurs when B100 or B20 are used as a substitute for petroleum diesel is for CO. Reductions in CO reach 34.5% when using B100. The effectiveness of B20 in reducing life cycle emissions of CO drops proportionately with the blend level. Biodiesel could, therefore, be an effective tool for mitigating CO in EPA's designated CO non-attainment areas¹⁴.

¹⁴ These are urban areas in the U.S. identified as not currently meeting National Ambient Air Quality Standards for levels of carbon monoxide.



**Figure 12: Life Cycle Air Emissions for B100 and B20
Compared to Petroleum Diesel Life Cycle Air Emissions**

B100 exhibits life cycle emissions of total particulates (TPM) that are 32.41% lower than those of the petroleum diesel life cycle. As with CO, the effectiveness of biodiesel in reducing TPM drops proportionately with blend level. This improvement in TPM emissions is a direct result of reductions in PM10 at the tailpipe of the bus. Tailpipe emissions of PM10 are 68% lower for urban buses operating on B100 versus petroleum diesel. PM10 emitted from mobile sources is a major EPA target because of its role in respiratory disease. Urban areas represent the greatest risk in terms of numbers of people exposed and level of PM10 present. Use of biodiesel in urban buses is potentially a viable option for controlling both life cycle emissions of TPM and tailpipe emissions of PM10¹⁵.

Biodiesel's life cycle produces 35% more THC than petroleum diesel's life cycle. This is in spite of the fact that tailpipe emissions of THC for B100 are 37% lower. The level of emissions of hexane that occur in the soybean crushing stage overshadows the tailpipe benefits¹⁶. In understanding the implications of the higher life cycle emissions, it is important to remember that emissions of hydrocarbons, as with all of the air pollutants discussed, have localized effects. In other words, it makes a difference *where* these emissions occur. The fact that biodiesel's hydrocarbon emissions at the tailpipe are lower may mean that

¹⁵ Among the options under consideration by EPA are regulations that would control levels of PM2.5, as opposed to PM10. PM2.5 includes particles of 2.5 microns or less in diameter. That is, EPA is focusing its attention on the very smallest particles in ambient air. Data collected in this study focus on PM10. While our results bode well for lowering levels of PM10, no information is available on the effect of biodiesel on this new class of smaller particles.

¹⁶ See section 9.1.4.3 Comparison of Life Cycle Air Emissions from Biodiesel and Petroleum Diesel for more details.